Bench-Scale Development and Testing of Rapid PSA for CO_2 Capture

University of South Carolina

catacel™ Driving Reaction Technology

Battelle The Business of Innovation

GRACE Davison

NETL Meeting, Pittsburg, PA, May 22, 2012

Overall Project Objectives

- design, develop and demonstrate a bench-scale process for the efficient and cost effective separation of CO_2 from flue gas using Pressure Swing Adsorption (PSA)
- goal to reduce energy consumption, capital costs, and environmental burdens with novel PSA cycle/flowsheet designs
- applicable to both large (500-1000 MW) and small (5-50 MW) capacity power plants, and industries with 10 to 100 times less CO_2 production

Process simulations and experiments, CFDs and experiments and complete flowsheet analyses being used for demonstrating and validating the concepts.

PSA Technology Advantages

- established, very large scale technology for other applications
- needs no steam or water; only electricity
- tolerant to trace contaminants; possibly with use of guard or layered beds
- zeolite adsorbent commercial and widely available
- increase in COE lower than other capture technologies
- beds can be installed under a parking lot

PSA Technology Challenges

- energy intensive, but better than today's amines; possibly overcome by novel designs
- today, very large beds required → implies large pressure drop → more power; possibly overcome by structured adsorbents and faster cycling
- large footprint; possibly overcome by underground installation and faster cycling → smaller beds
- high capitol cost; possibly overcome by faster cycling → smaller beds

Key PSA Technology Project Challenge

- although a commercial tri-sieve zeolite could be used today in an efficient PSA cycle, it would only minimize to some extent the pressure drop issues, but not the adsorbent attrition and mass transfer issues
- so, the key challenge of this project is to develop a structured adsorbent around an efficient PSA cycle that exhibits a high enough packing density to allow the fastest possible cycling rate (→ smallest possible beds), while improving pressure drop and mass transfer issues and eliminating attrition issues

Today, I would like to answer four questions:

How did we get to this point?

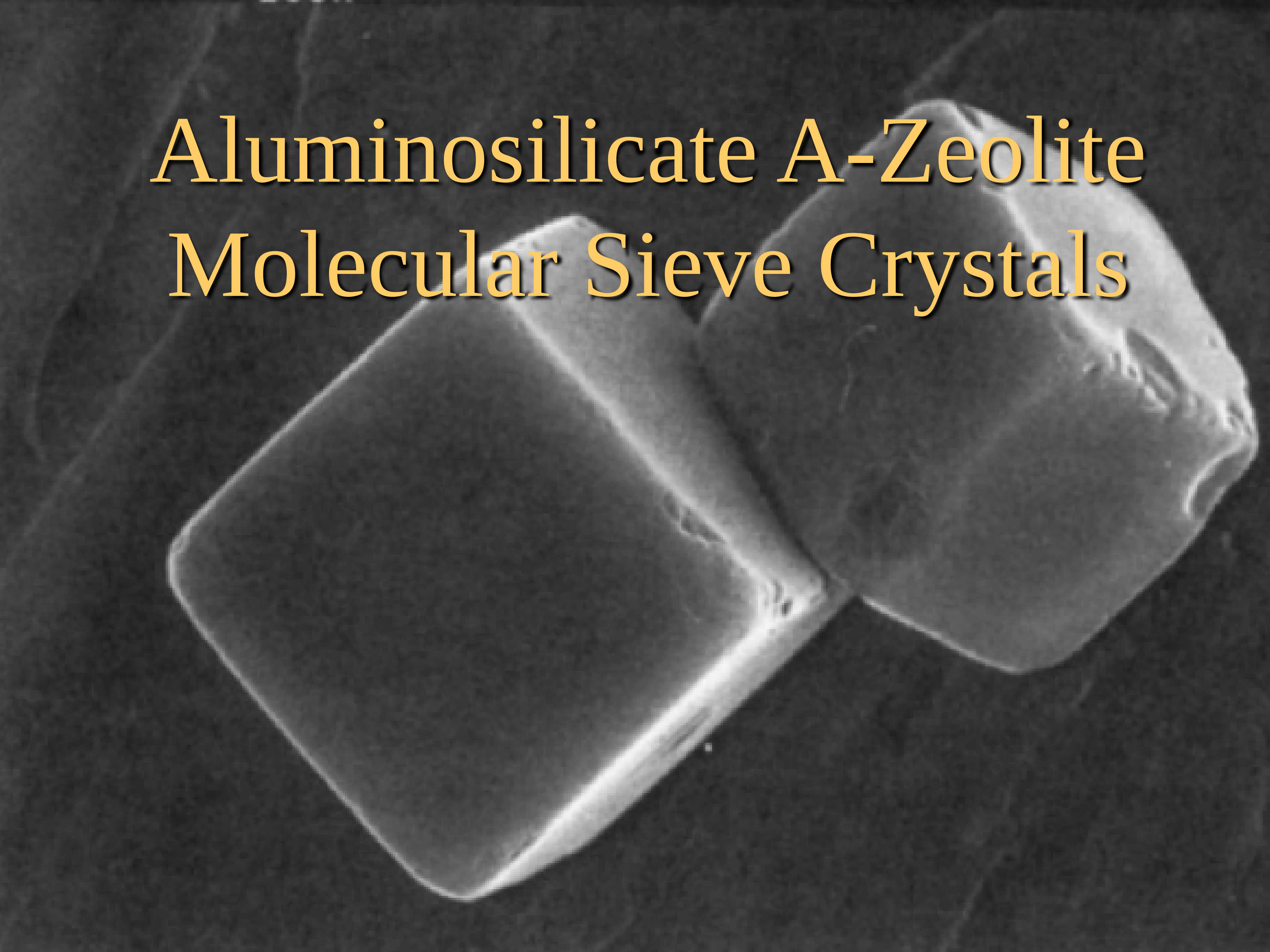
Where are we now?

Where are we going?

How are we going to get there?

How does pressure swing adsorption work?

Aluminosilicate A-Zeolite Molecular Sieve Crystals



Aluminosilicate A-Zeolite Molecular Sieve Cage

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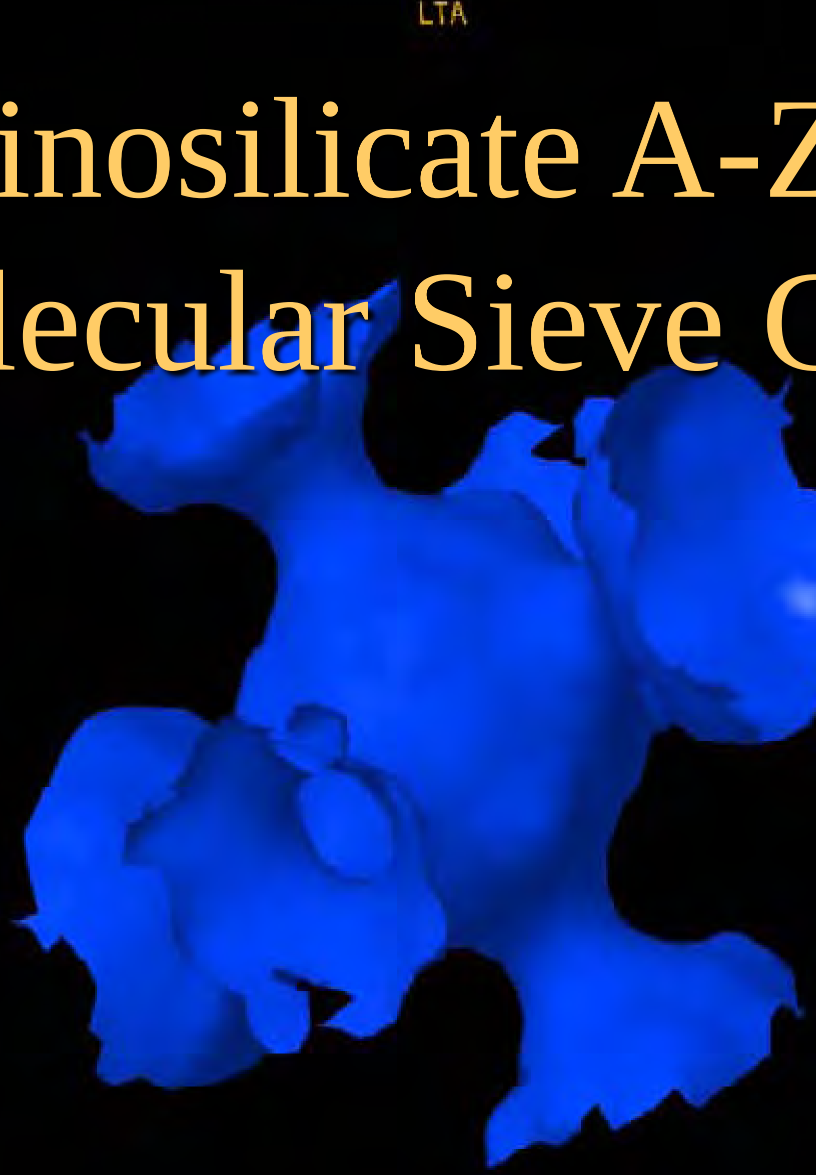
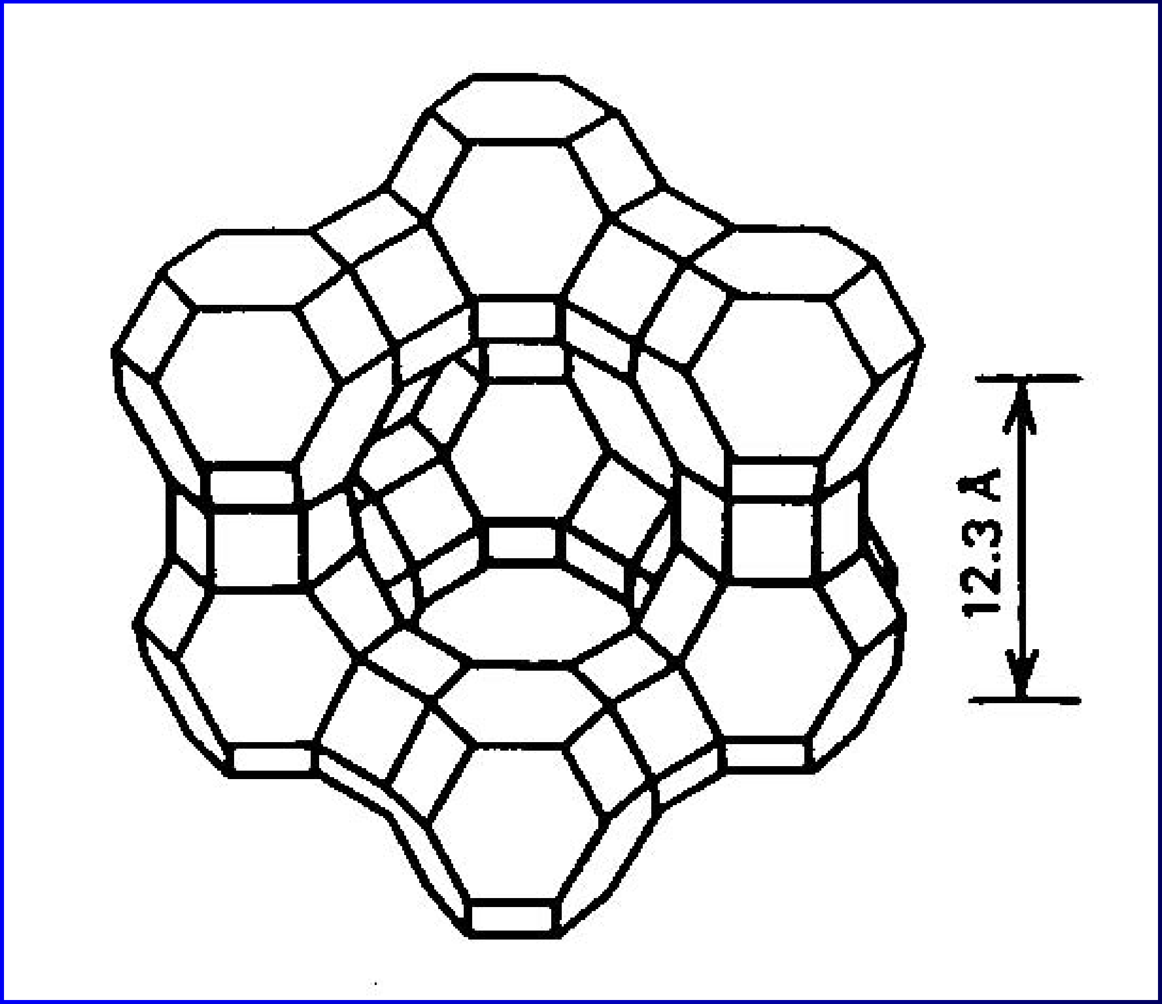
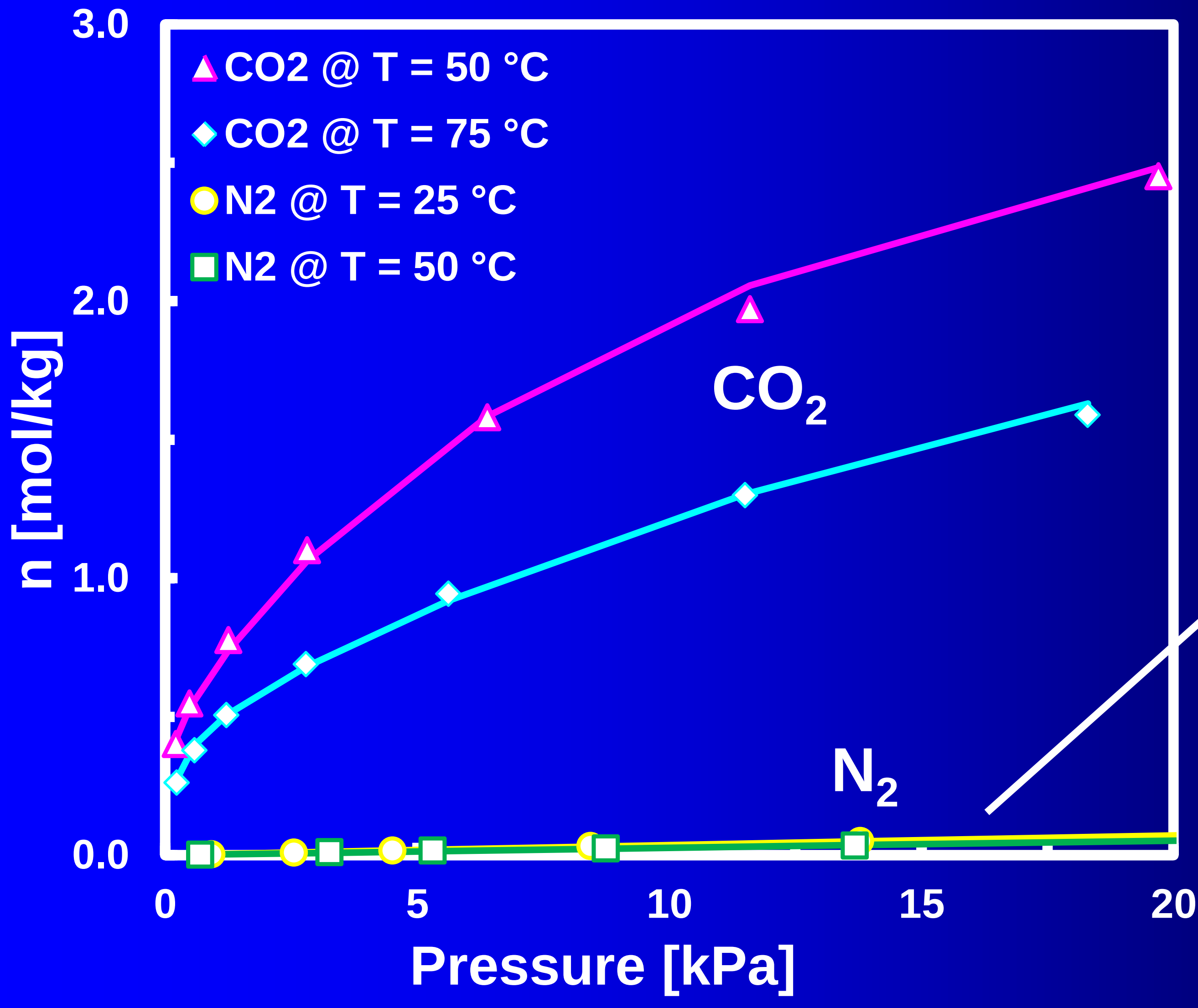


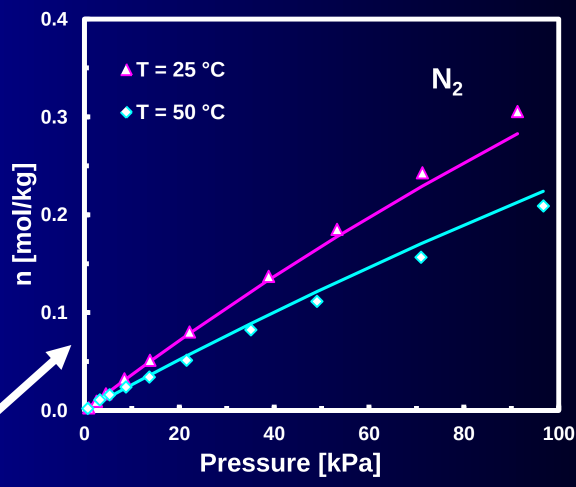
Aluminosilicate X Zeolite Molecular Sieve Cage



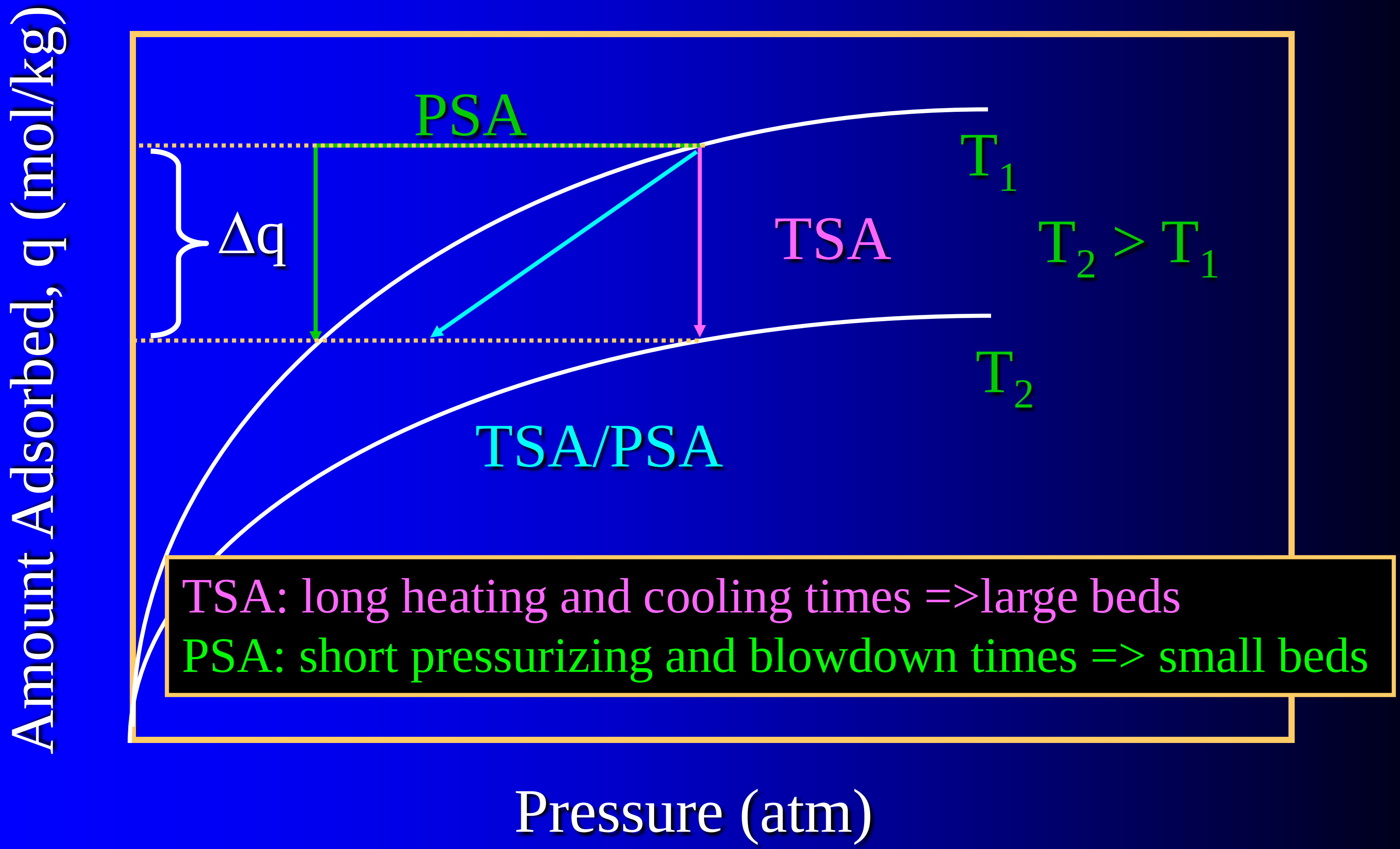
Aluminosilicate Zeolite Molecular Sieve Pellets

Adsorption Isotherms for CO_2 and N_2 on 13X Zeolite





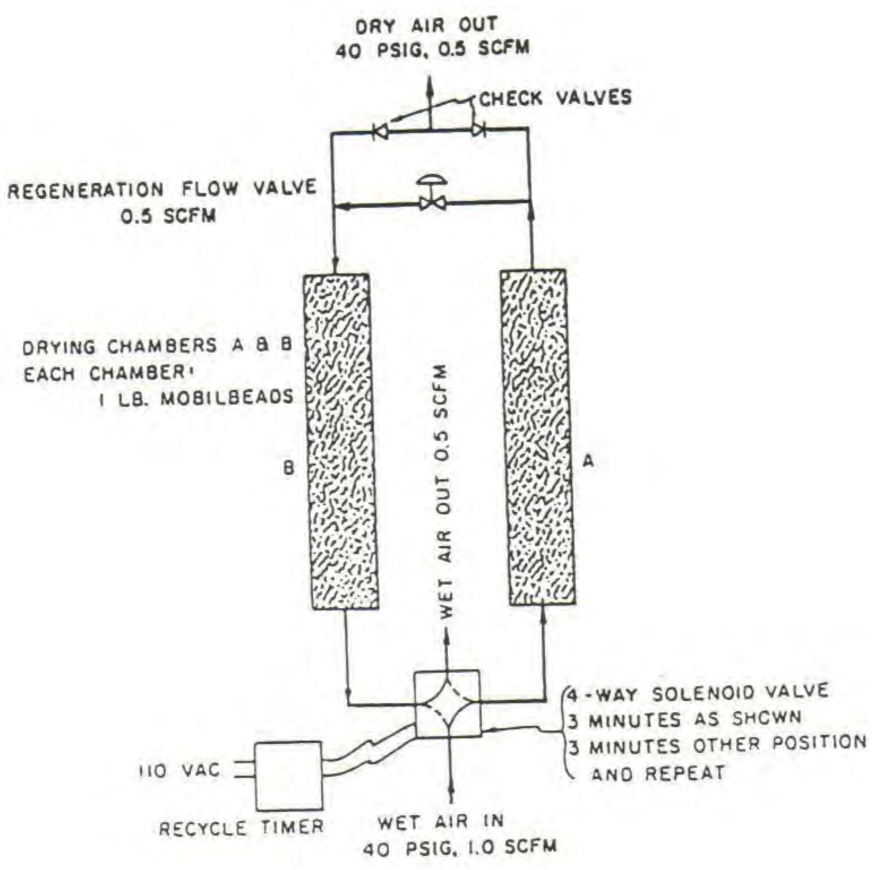
Pressure and Thermal Swing Adsorption Concepts Based on the Adsorption Isotherm



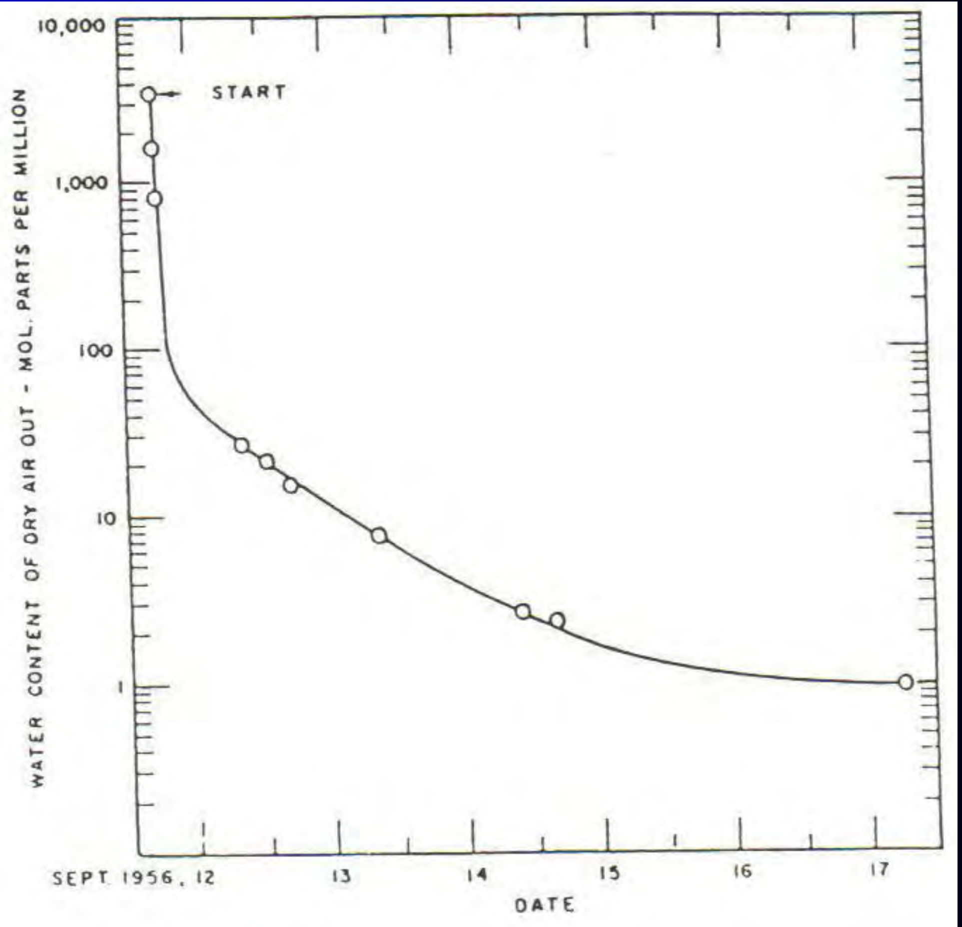
Behavior of Typical PSA Process

Approach to Periodic State

Twin-Bed Silica Gel Air Dryer Operating a Simple 4-Step PSA Cycle



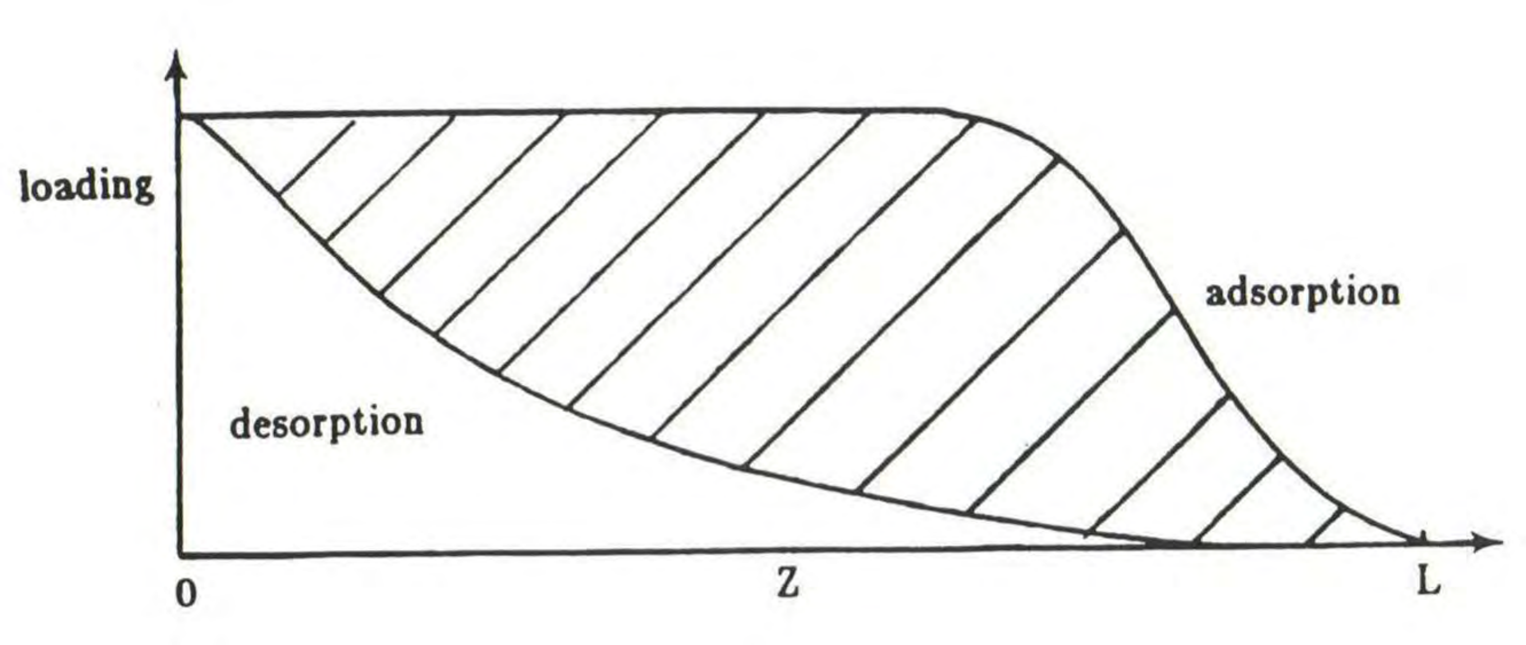
(a)



Same behavior for nearly all PSA systems no matter the application.

Periodic PSA Process Behavior

Typical loading in a PSA column, for example, at the end of the adsorption and desorption (or regeneration) steps, showing the working capacity of the bed.

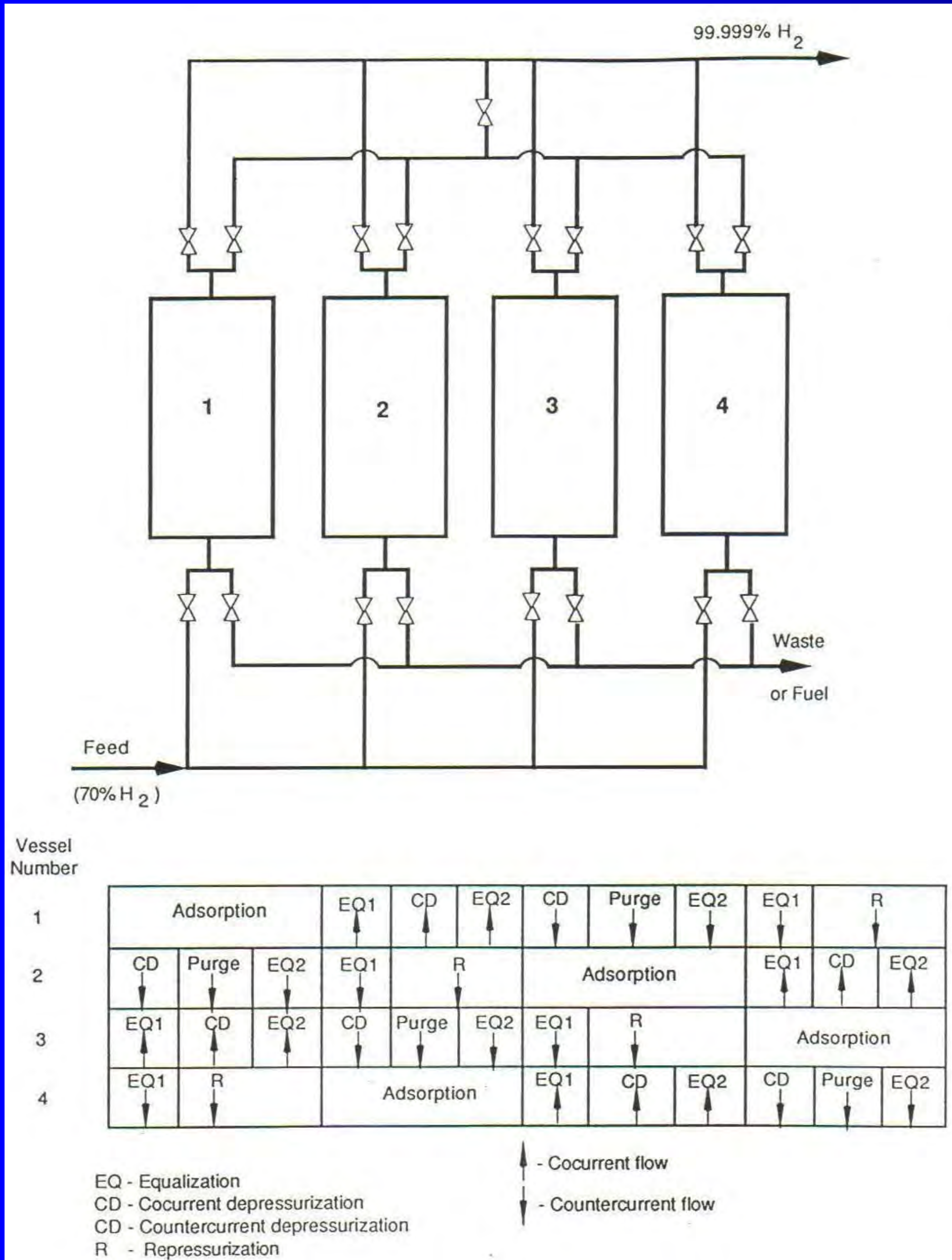


The loading in the column slowly builds up with time, is never completely regenerated, and after many cycles attains a periodic state.

Traditional PSA Cycle Steps

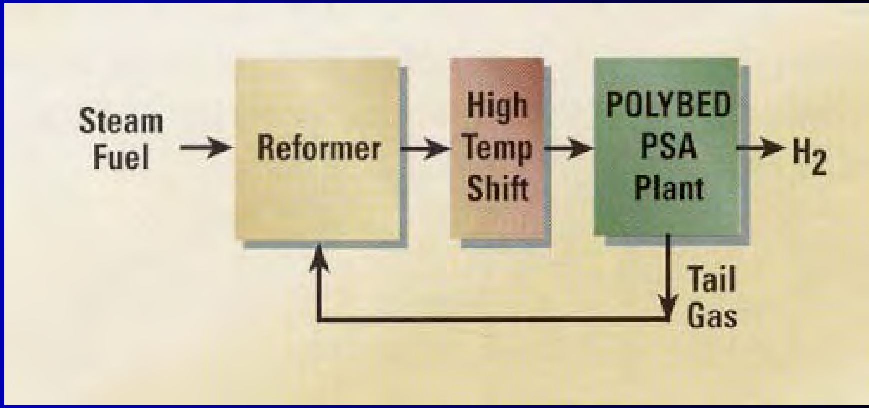
- six basic steps for conventional PSA
  - pressurization, e.g., with feed or light product
  - high pressure feed with light product production
  - depressurization or blowdown (cocurrent or countercurrent to the feed)
  - desorption at low pressure with light product purge (light reflux), evacuation or both
  - pressure equalization between beds
  - high pressure rinse with heavy product (purge or heavy reflux) following feed

Typical Cycle Sequencing for a Four-Bed PSA Hydrogen Purification Plant



These cycles can become very complicated, with the state-of-the-art PSA hydrogen purification plant now operating 16 interconnected beds!

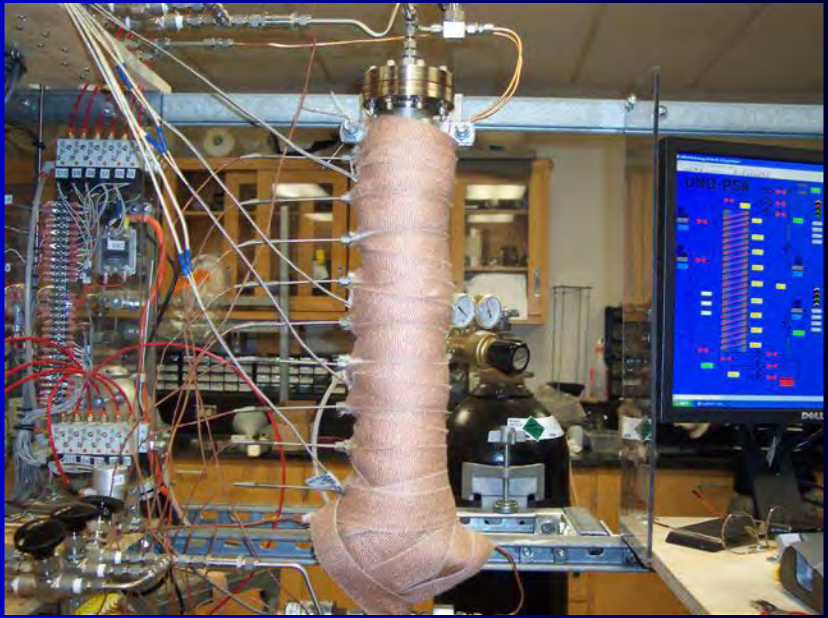
PSA: UOP Polybed Hydrogen Production Unit




How did we get to this point?

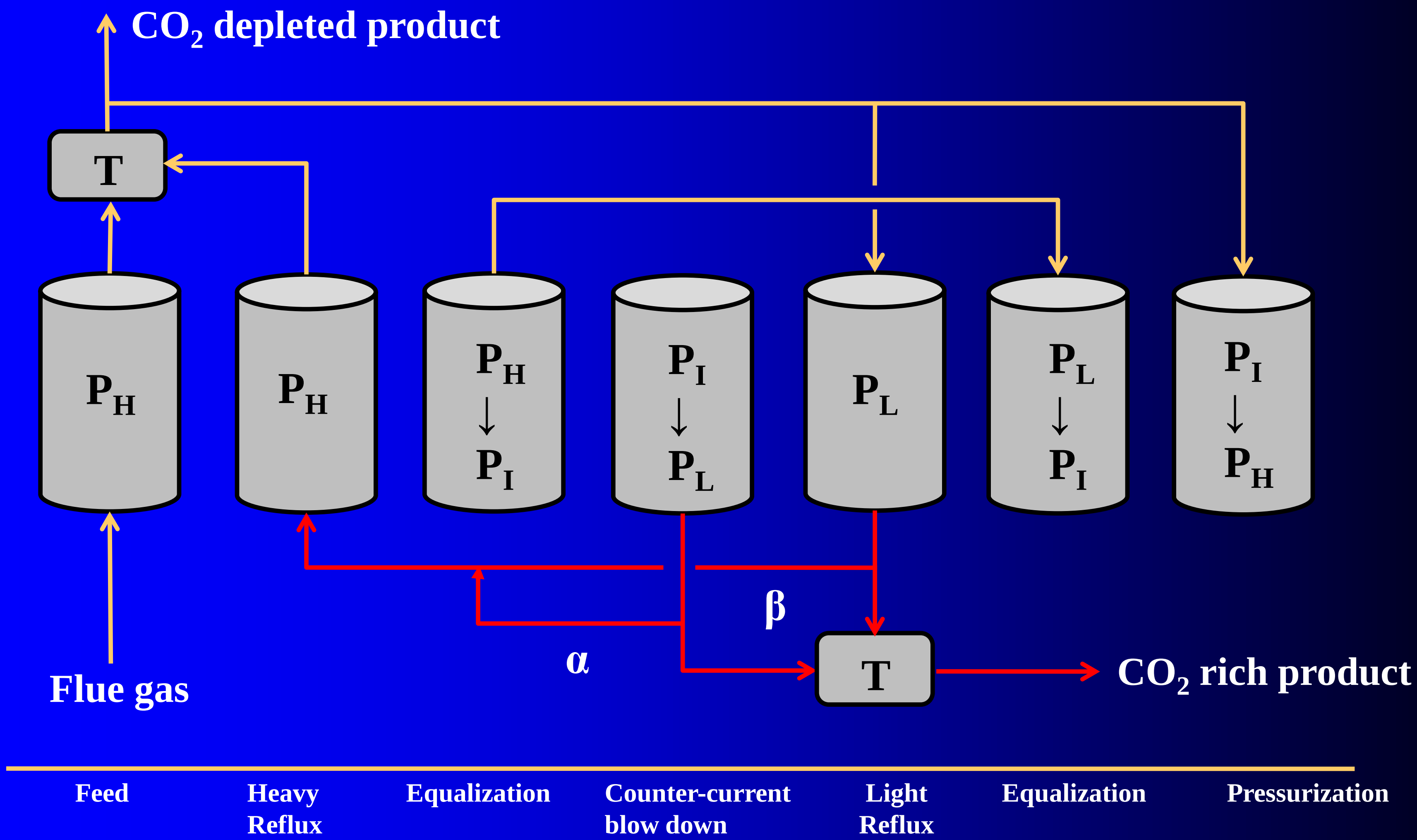
1-Bed PSA Experiments to Validate the Dynamic Adsorption Process Simulator

VS



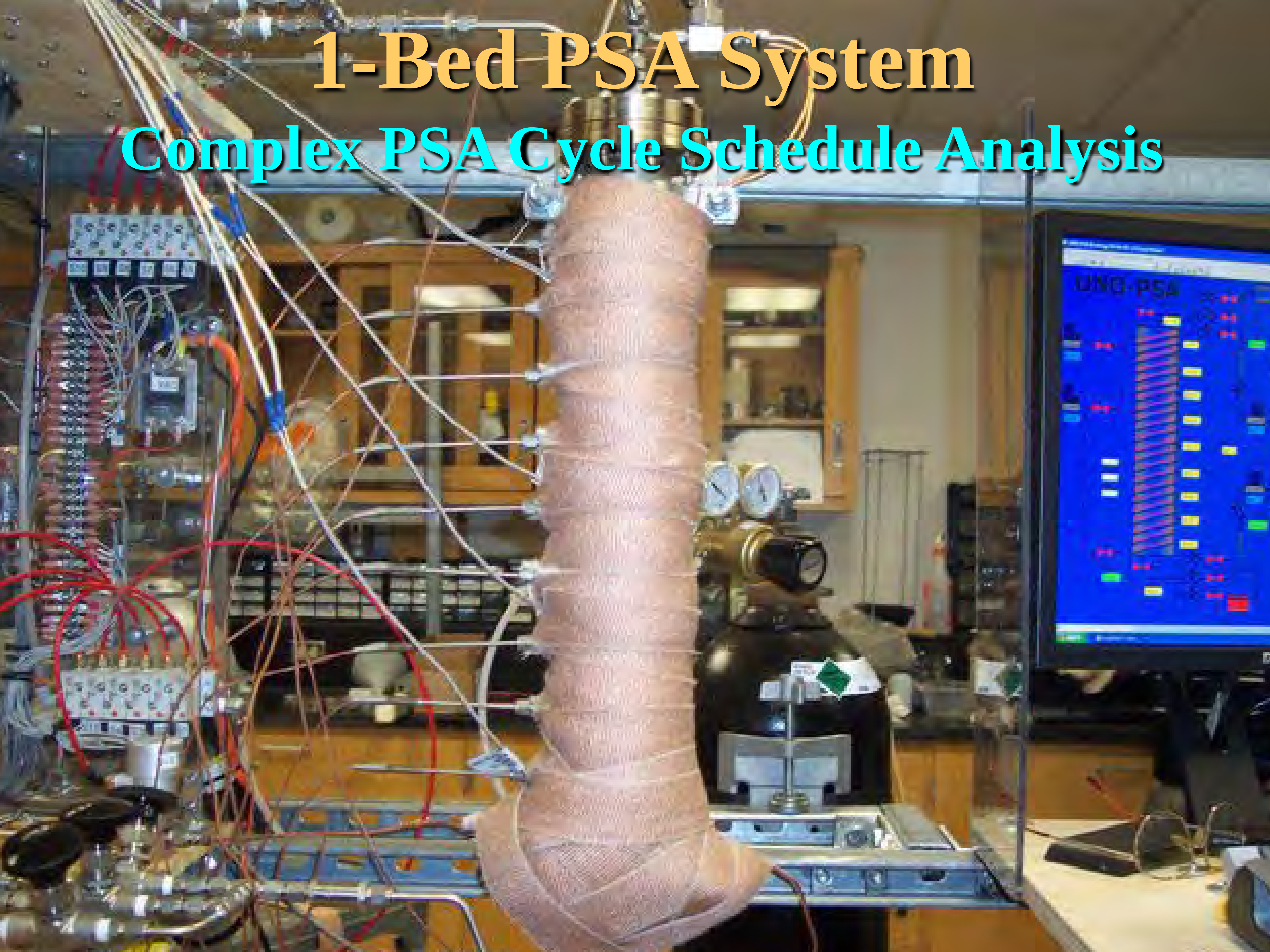
Typical Cycle Steps for PSA Operation

Snapshot of Multi-Bed PSA System

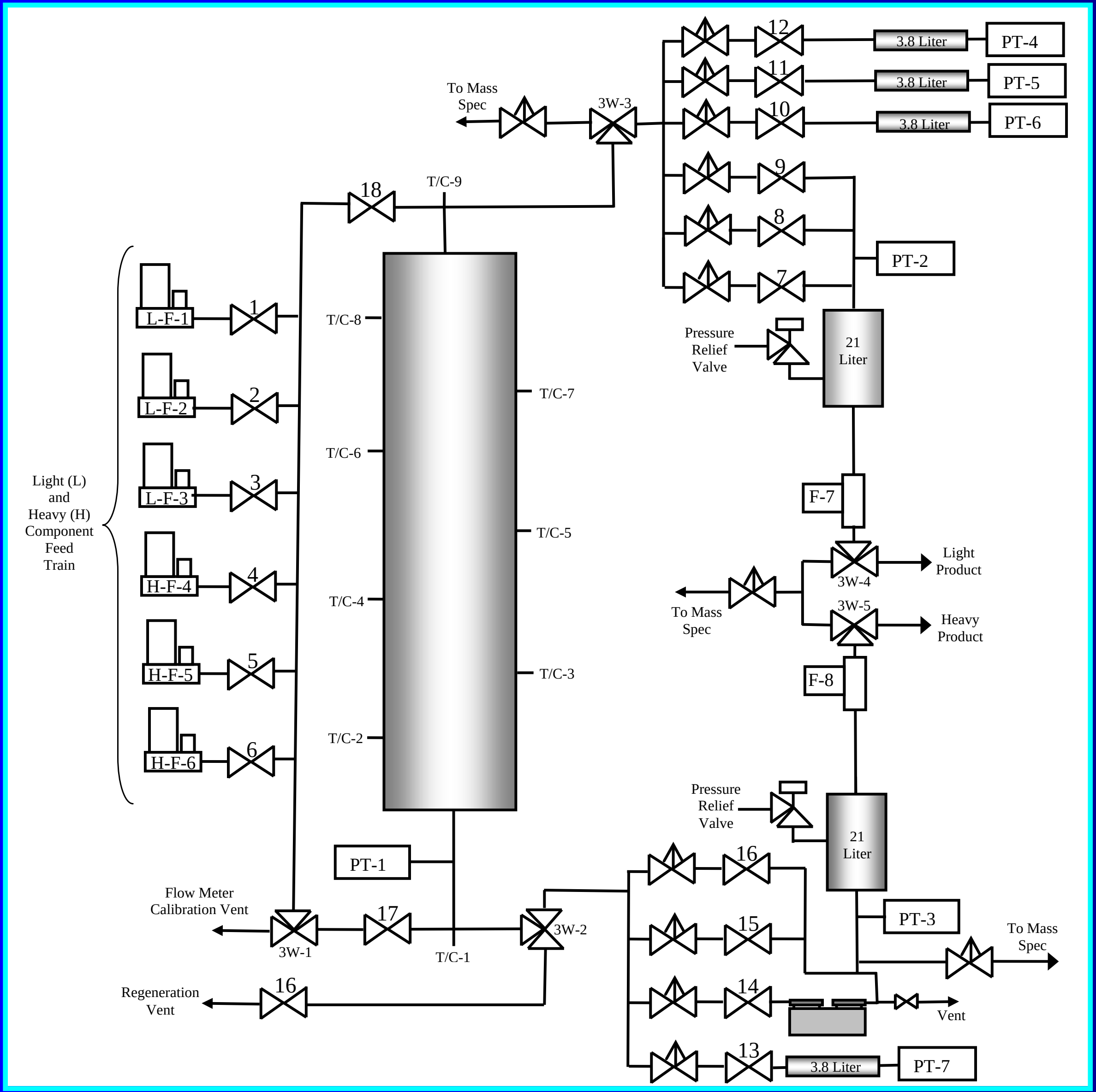


1-Bed PSA System

Complex PSA Cycle Schedule Analysis



1-Bed PSA System

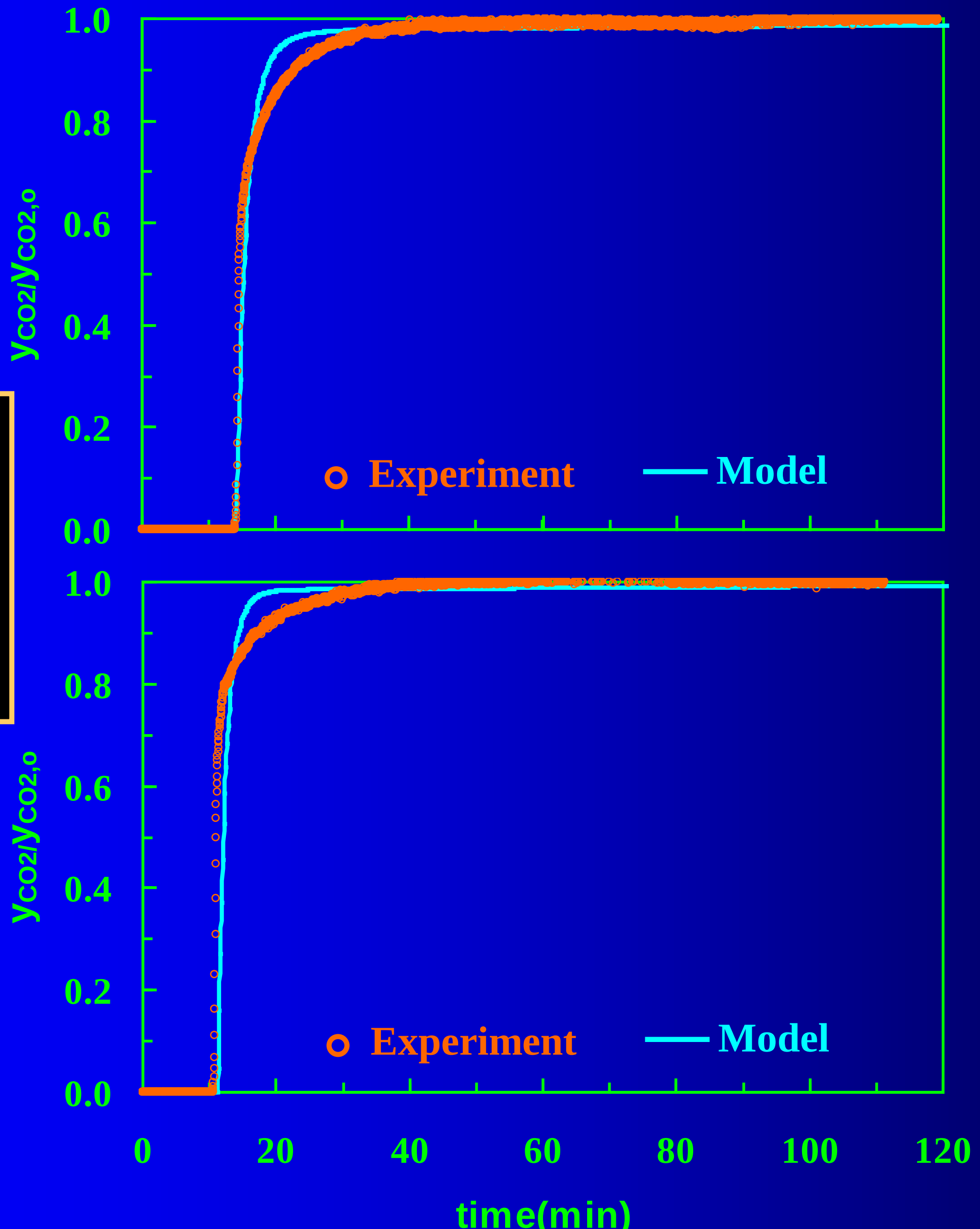


Experimental Setup

- Breakthrough runs
- Pure gas cycling
- PSA cycles (any possible combination of cycle steps)

CO_2 Breakthrough Experiments on 13X Zeolite

- Mass Transfer Coefficient Determination
- Isotherm Validation



30% CO_2

70% He

Flow = 10 SLPM

Pressure = 25 psia

Temperature = 25°C

40% CO_2

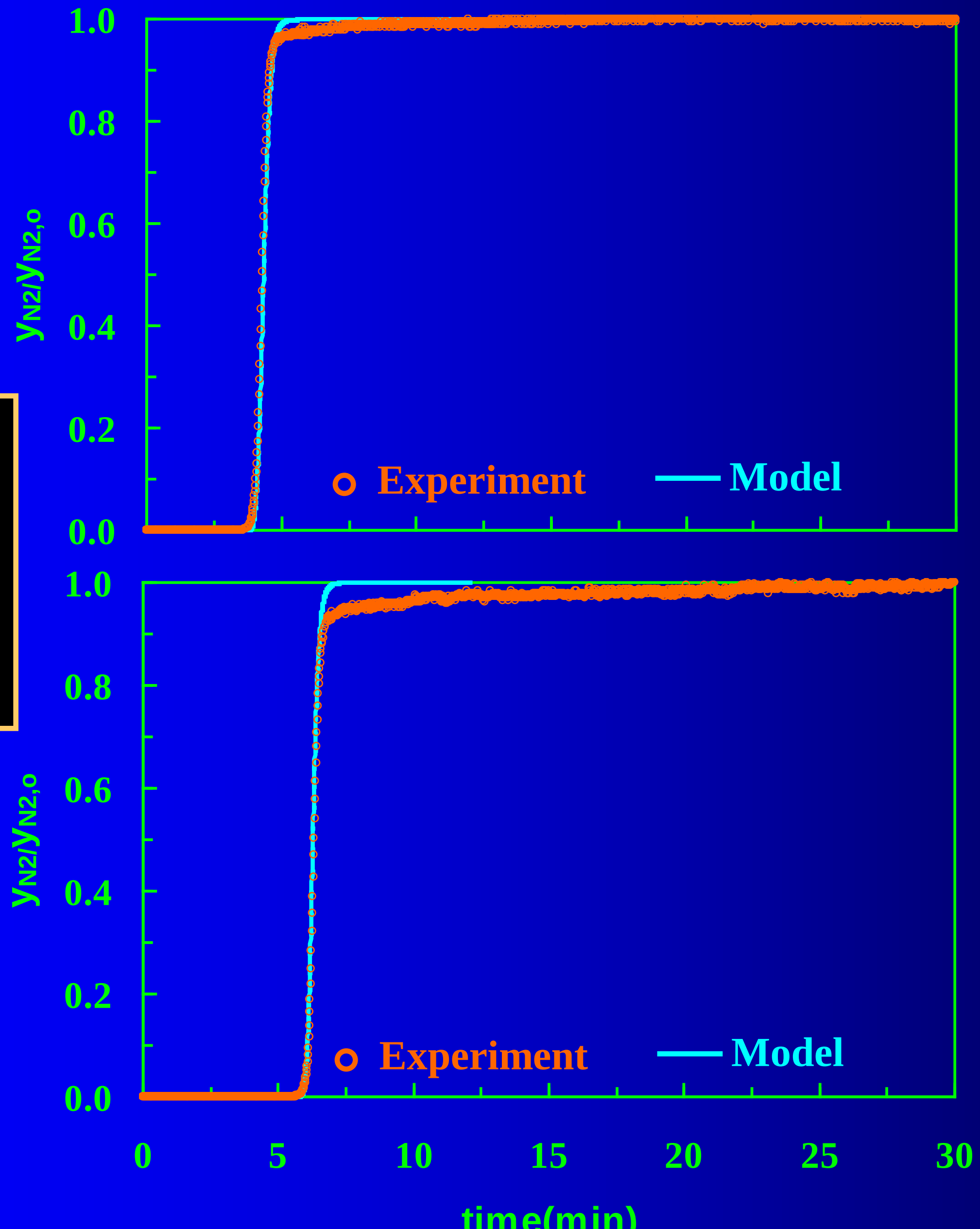
60% He

Flow = 10 SLPM

Pressure = 25 psia

Temperature = 25°C

N_2 Breakthrough Experiments on 13X Zeolite



20% N_2

80% He

Flow = 2.55 SLPM

Pressure = 25 psia

Temperature = 25°C

30% N_2

70% He

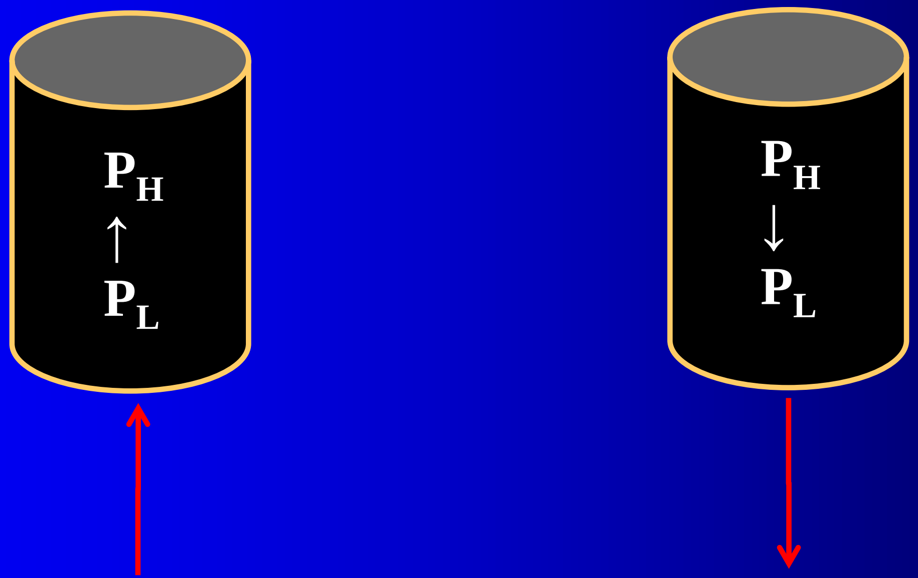
Flow = 1.67 SLPM

Pressure = 25 psia

Temperature = 25°C

- Mass Transfer Coefficient Determination
- Isotherm Validation

Two-Step CO_2 and N_2 Cycling Experiments



Pure CO_2 or N_2 Feed	Pure CO_2 or N_2 Effluent
Pressurization	**Counter-Current Blowdown**

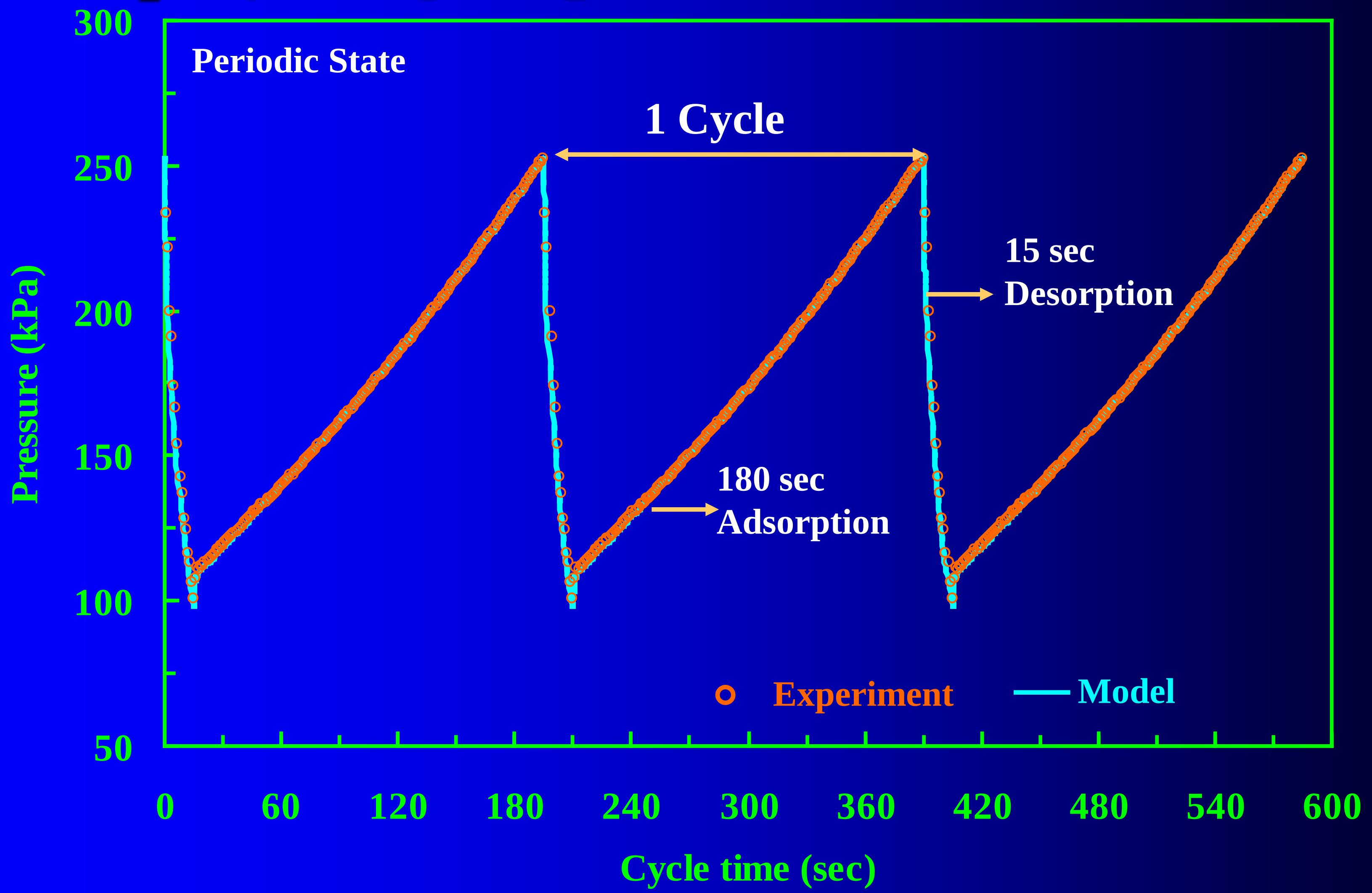
Information Obtained

a) Validation of Single Component Isotherms

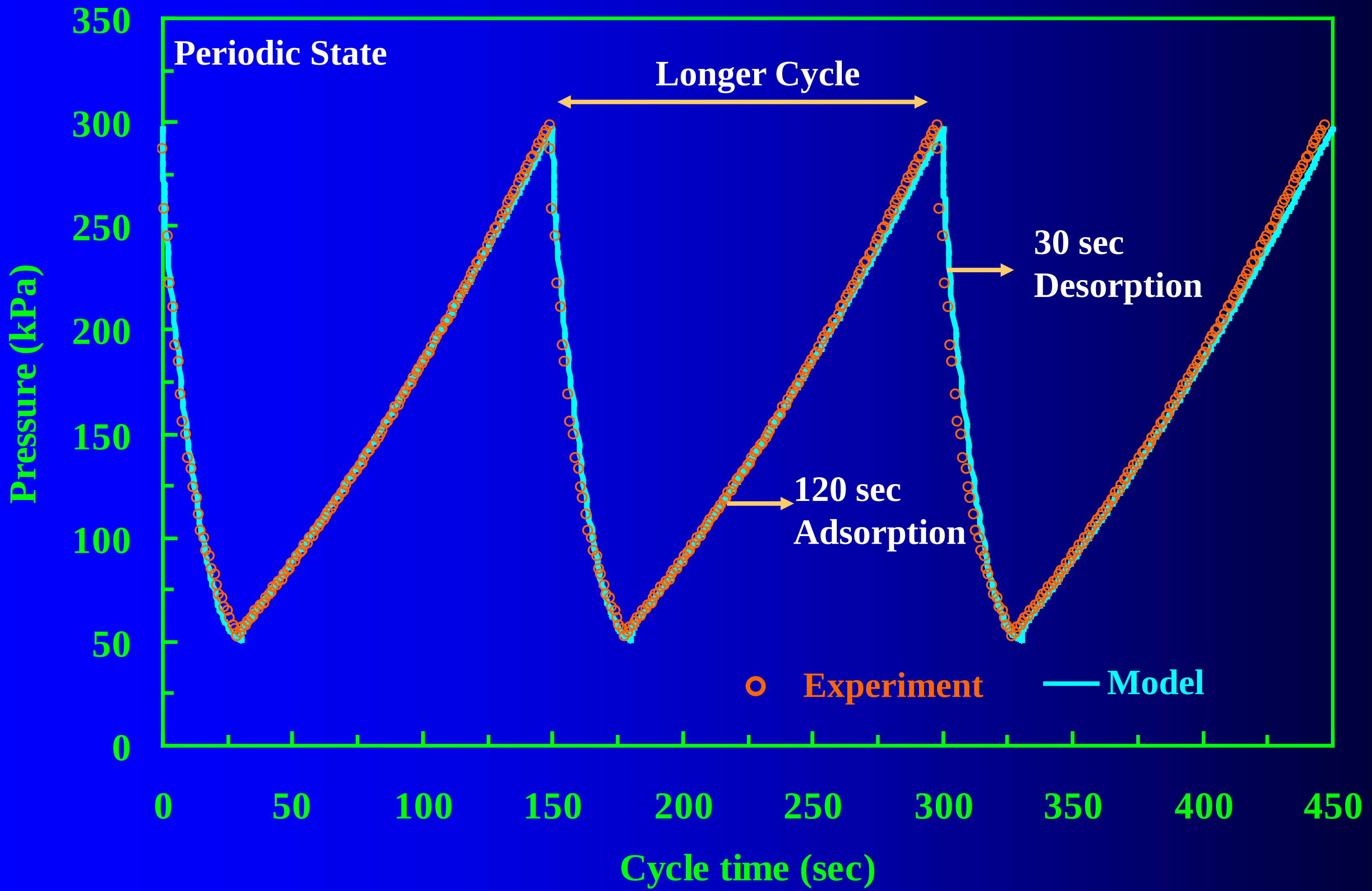
b) Validation Adsorption/Desorption Mass Transfer Coefficients

c) Determination of Valve C_v

CO_2 Cycling Experiments of 13X Zeolite

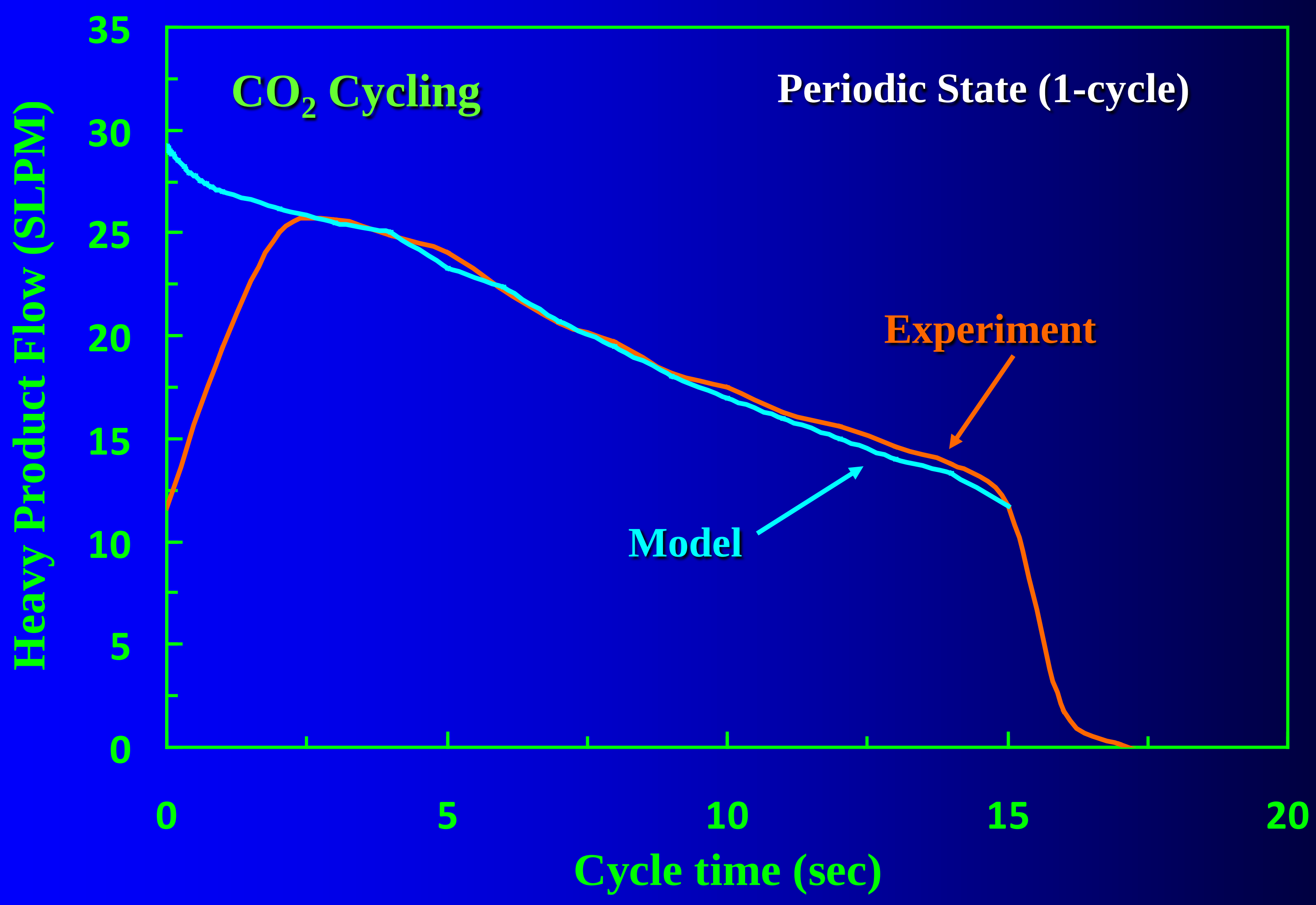


N_2 Cycling Experiments of 13X Zeolite



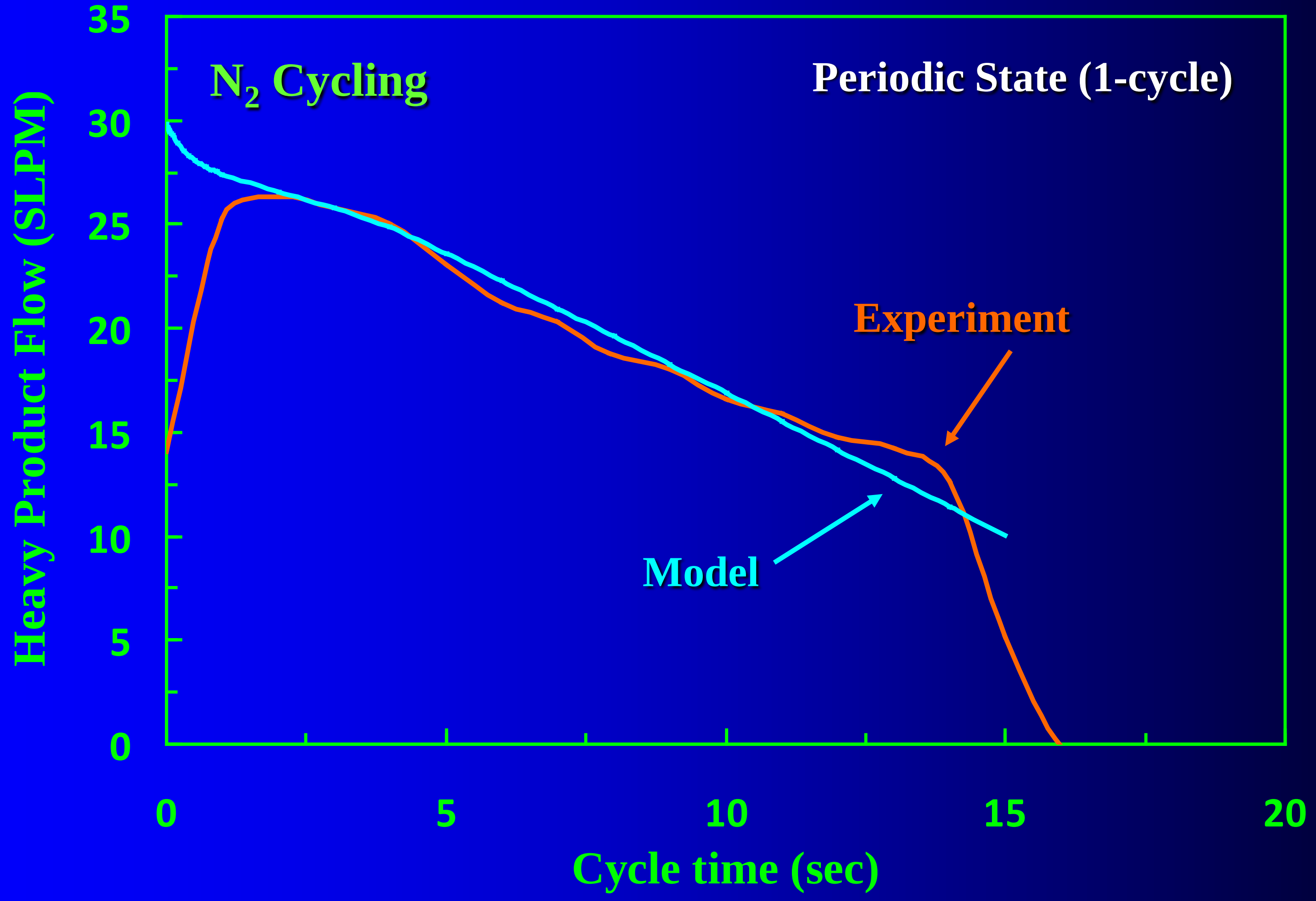
Pure Gas Cycling Experiments on 13X Zeolite

Heavy Product Flow Prediction



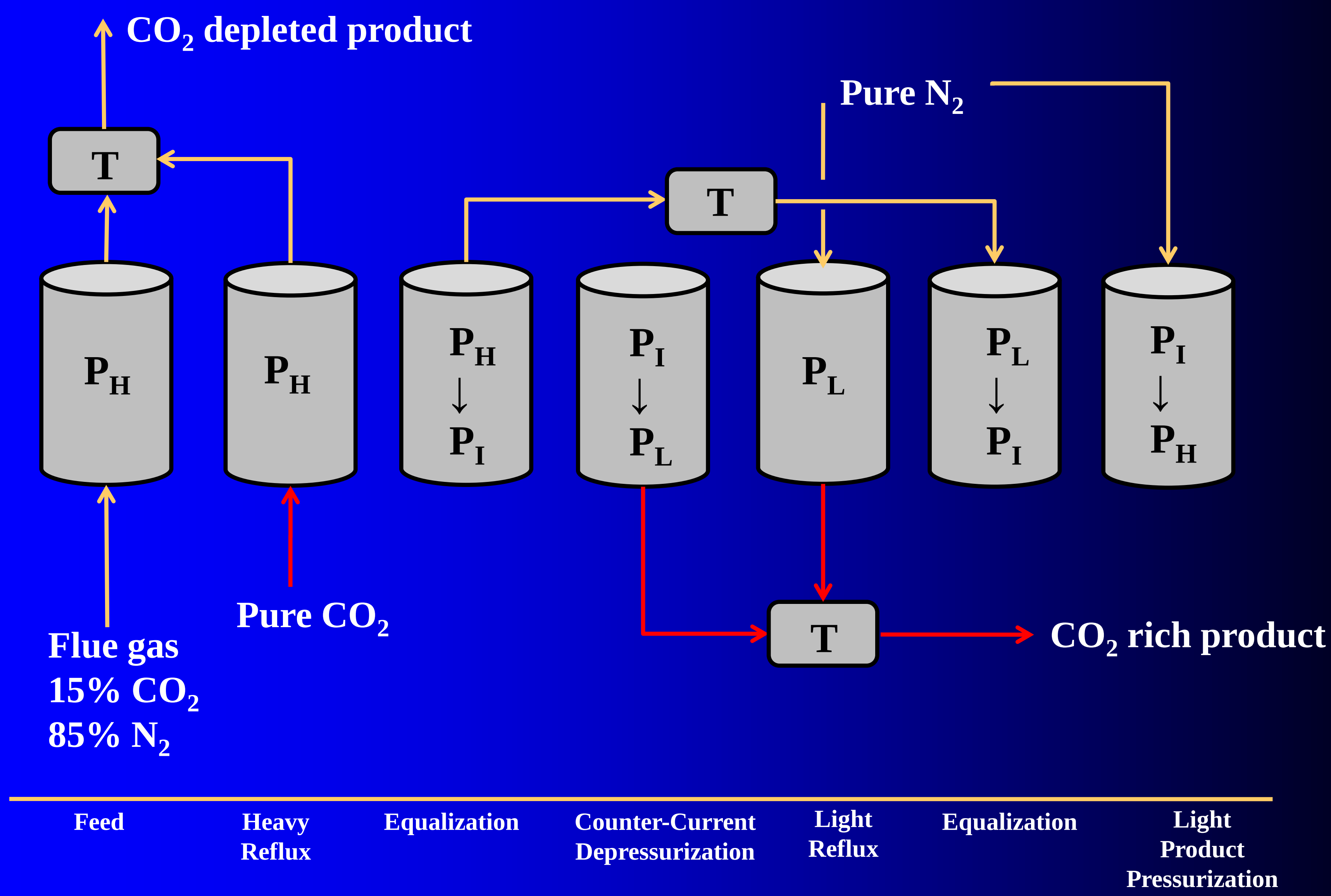
Pure Gas Cycling Experiments on 13X Zeolite

Heavy Product Flow Prediction



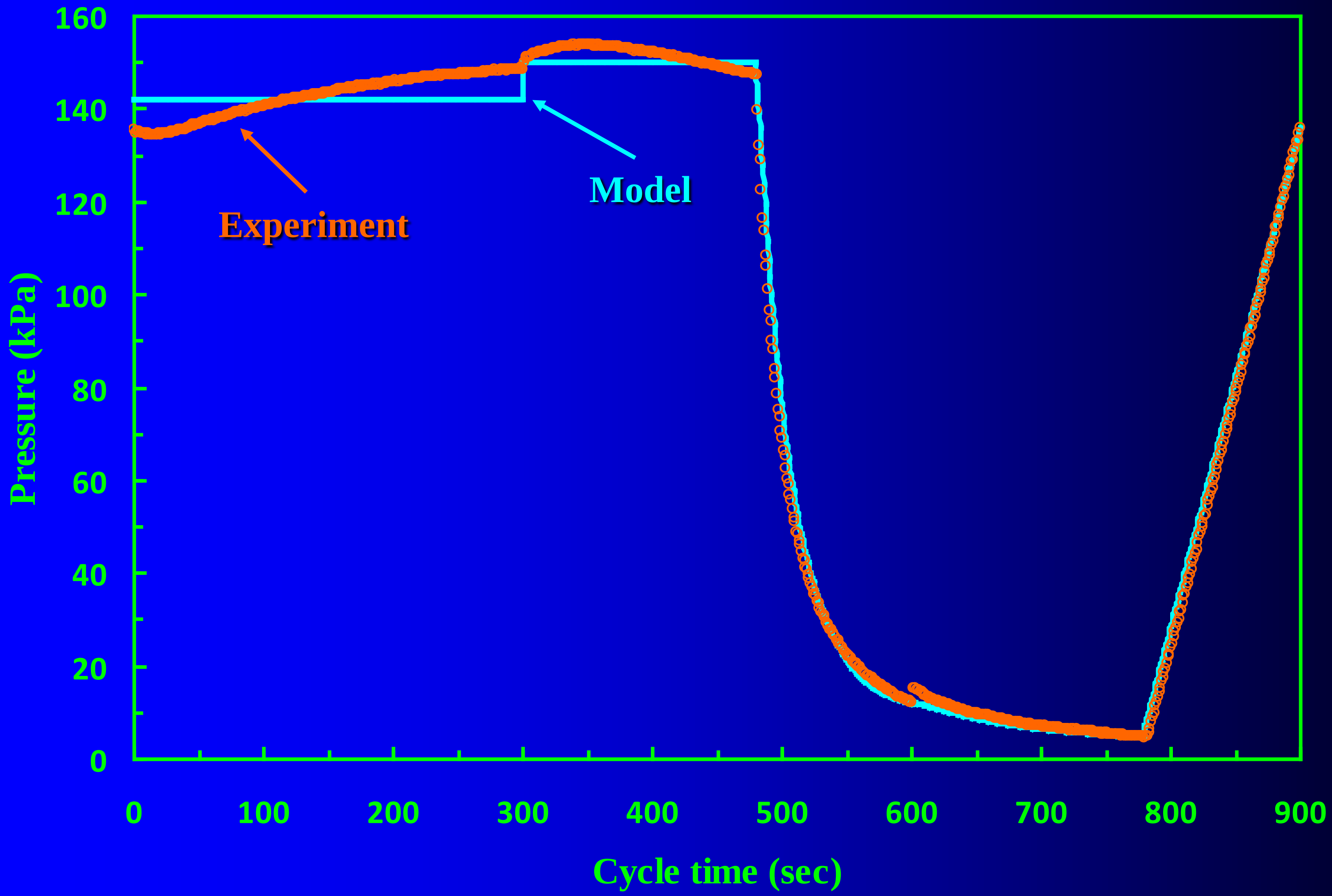
Cycle Translation from Multi-Bed to 1-Bed PSA Operation

1-Bed Experimental System



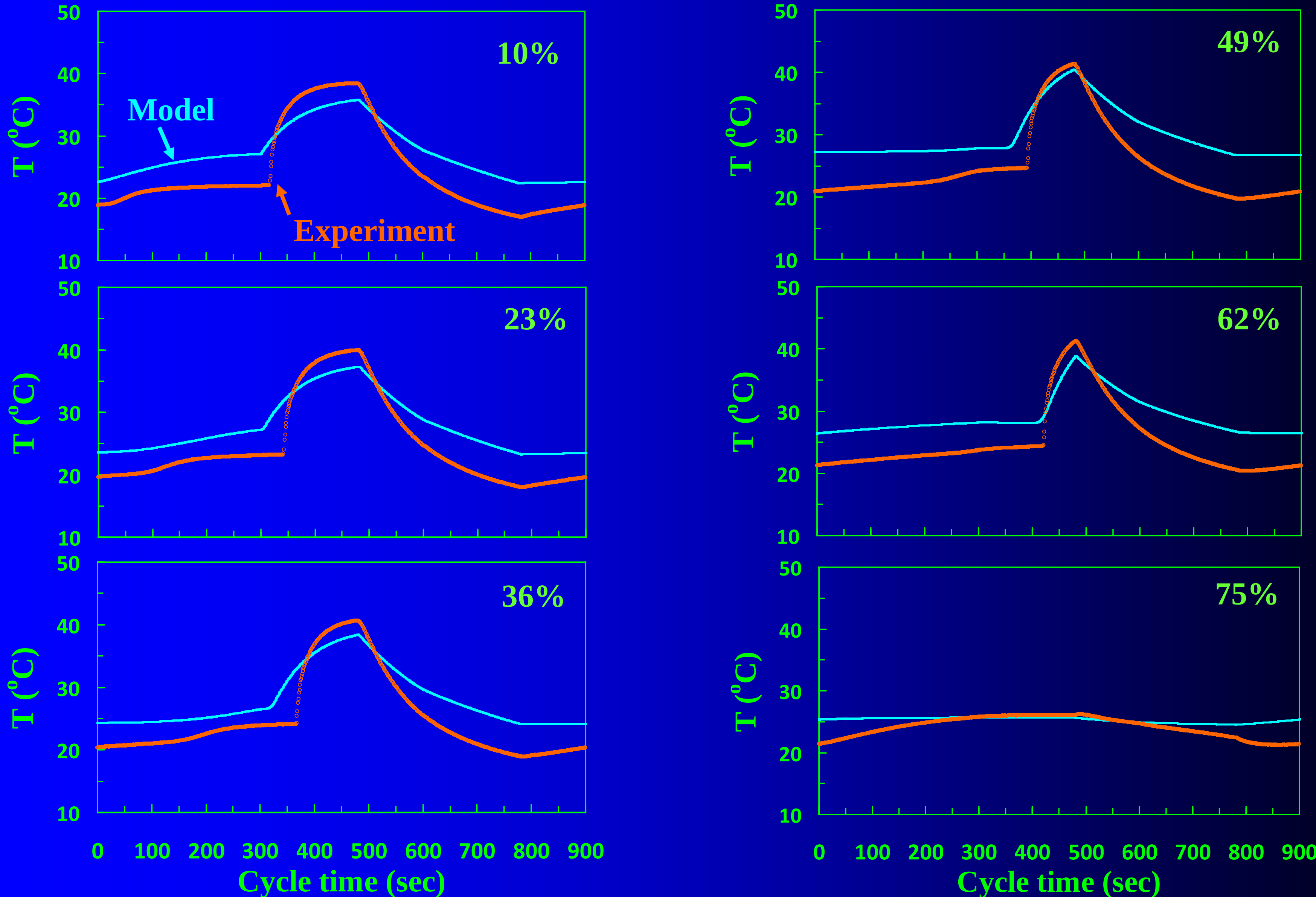
Typical 1-Bed PSA Experiment

Pressure Profile Matching



1-Bed PSA Experiment

Temperature Profile Prediction

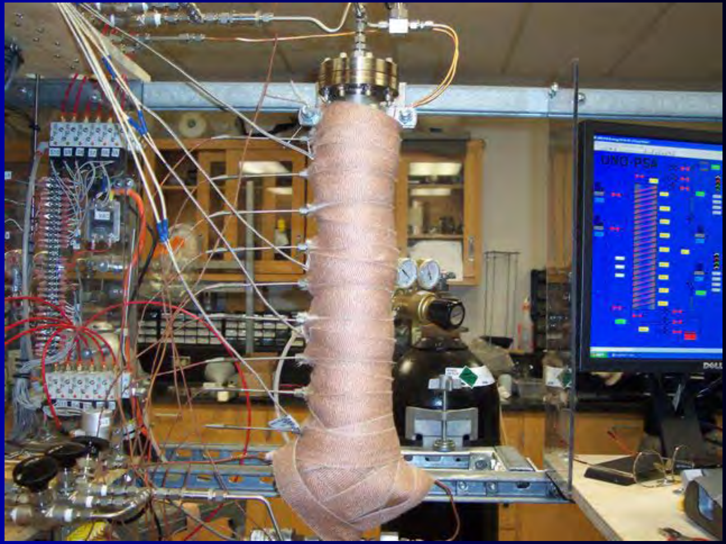


1-Bed PSA System: Experimental Results

Run	CO_2 Feed Concentration in N_2 (%)	Feed Throughput (L STP/hr/kg)	High Pressure (P_H) (psia)	Π (P_H / P_L)	T (°C)	Cycle Time (sec)	CO_2 Purity (%)	CO_2 Recovery (%)	N_2 Purity (%)	N_2 Recovery (%)
1	15	150	22.3	37	25.2	900	**94.1**	**90.9**	93.7	96.0
2	15	150	22.1	44	24.3	900	**93.9**	**92.9**	95.1	95.7
3	15	150	22.4	45	25.2	900	**91.5**	**93.2**	95.6	94.5
4	15	150	22.0	51	23.6	900	**95.9**	**90.3**	93.3	97.2

- numerous cycle schedules studied with different relative step times of individual cycle steps
- CO_2 recoveries and purities > 90%
- various combinations of process parameters and cycle steps giving high CO_2 recoveries and purities
  - understanding of interplay between them becoming crucial

Mathematical Modeling and Process Simulation



Dynamic Adsorption Process Simulator (DAPS)

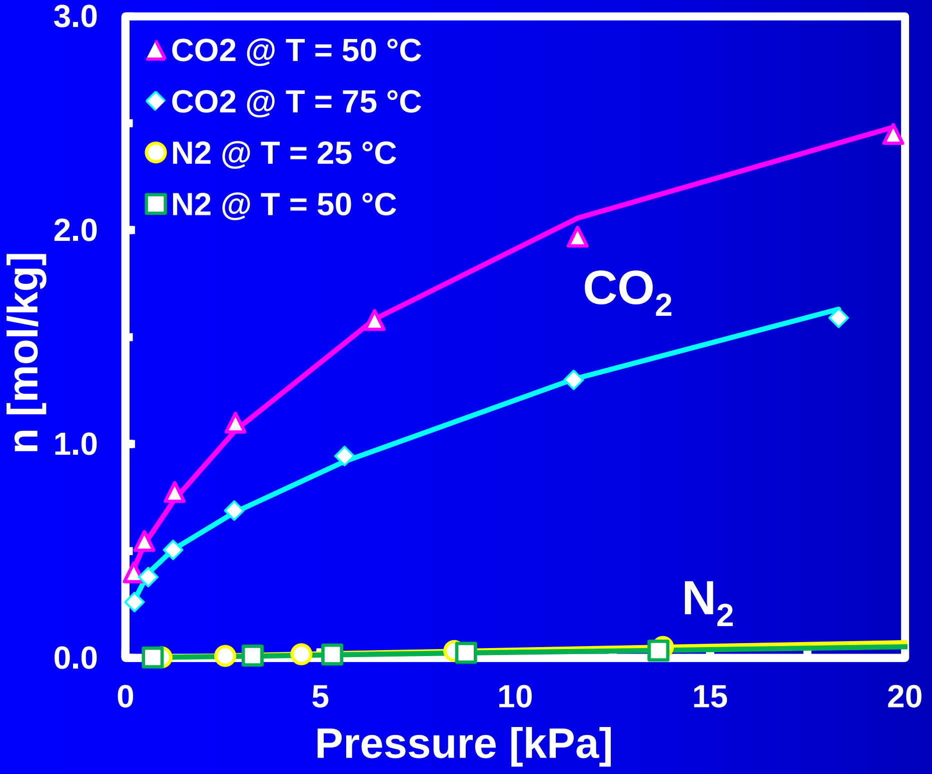
- multiple absorbent layers and multiple columns
- column pressure drop
- entering and exiting flows defined by constant flow, valve equations, or choke flow approaches (isentropic, fanno, etc)
- valve equations with time dependent coefficients for rotary valves
- interaction with other processes: cabin, distillation units, etc
- simultaneous feed, exit, pressure varying steps thru multiple ports
- ability to handle large P ratios and v's associated with deep vacuum systems
- multiple tanks dynamically modeled as continuously stirred vessels
- separators for condensable gases from products, recycles and refluxes
- inclusion of reactive processes for hybrid systems and gas compressibility corrections
- pressure implicit and explicit isotherms and dynamic transport models for specific diffusional processes

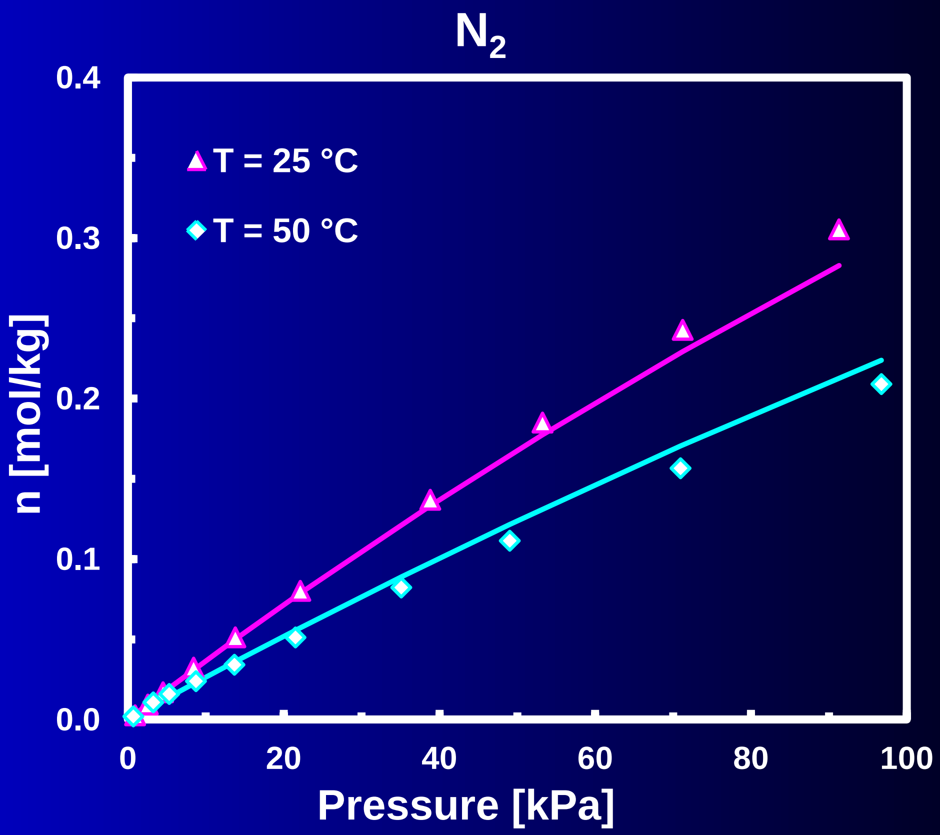
Cycle Schedule for a 16-Bed PSA H_2 Plant

Whysall, et al., USP 6,210,466 (2001)

1	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	
2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	
3	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE	E4	
4	PU	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE
5	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE
6	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE
7	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE
8	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PU
9	DU	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP	DU
10	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	PP
11	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	E3	E4	
12	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION	E1	E2	
13	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION	
14	ADS	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION
15	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADSORPTION
16	ADSORPTION	E1	E2	E3	E4	PP	DUMP	PURGE	E4	E3	E2	E1	RP	ADS

Adsorption Isotherms of CO_2 and N_2 on 13X Zeolite





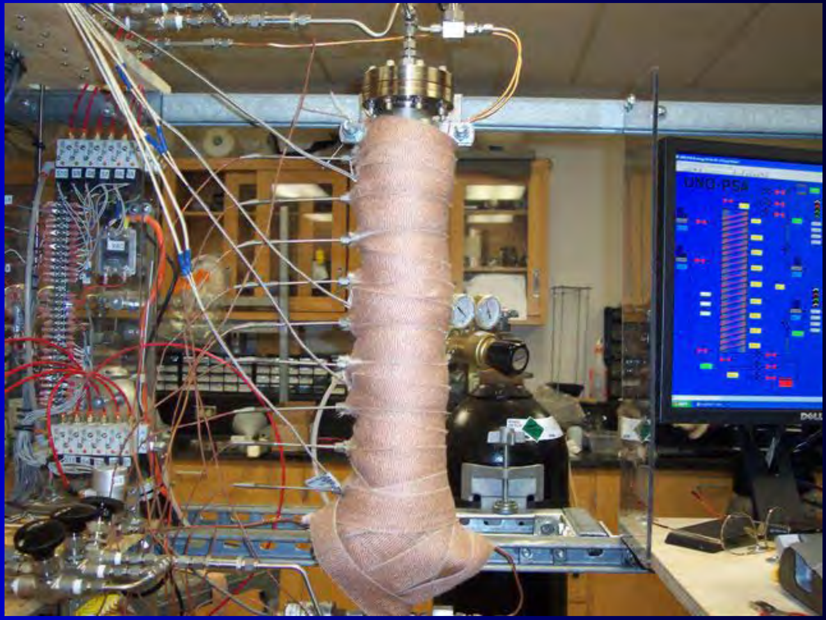
Heat of Adsorption for CO_2 is 40.73 kJ/mol

Heat of Adsorption for N_2 is 10.30 kJ/mol

PSA Process Simulator Validation with 1-Bed PSA Experiment

	CO_2 Feed Concentration in N_2 (%)	Feed Throughput (L STP/hr/kg)	T (^oC)	Cycle Time (sec)	CO_2 Purity (%)	CO_2 Recovery (%)	N_2 Purity (%)	N_2 Recovery (%)
Experiment	15	150	25.2	900	94.1	90.9	93.7	96.0
Model	15	150	25.4	900	93.2	91.5	93.5	97.1

VS

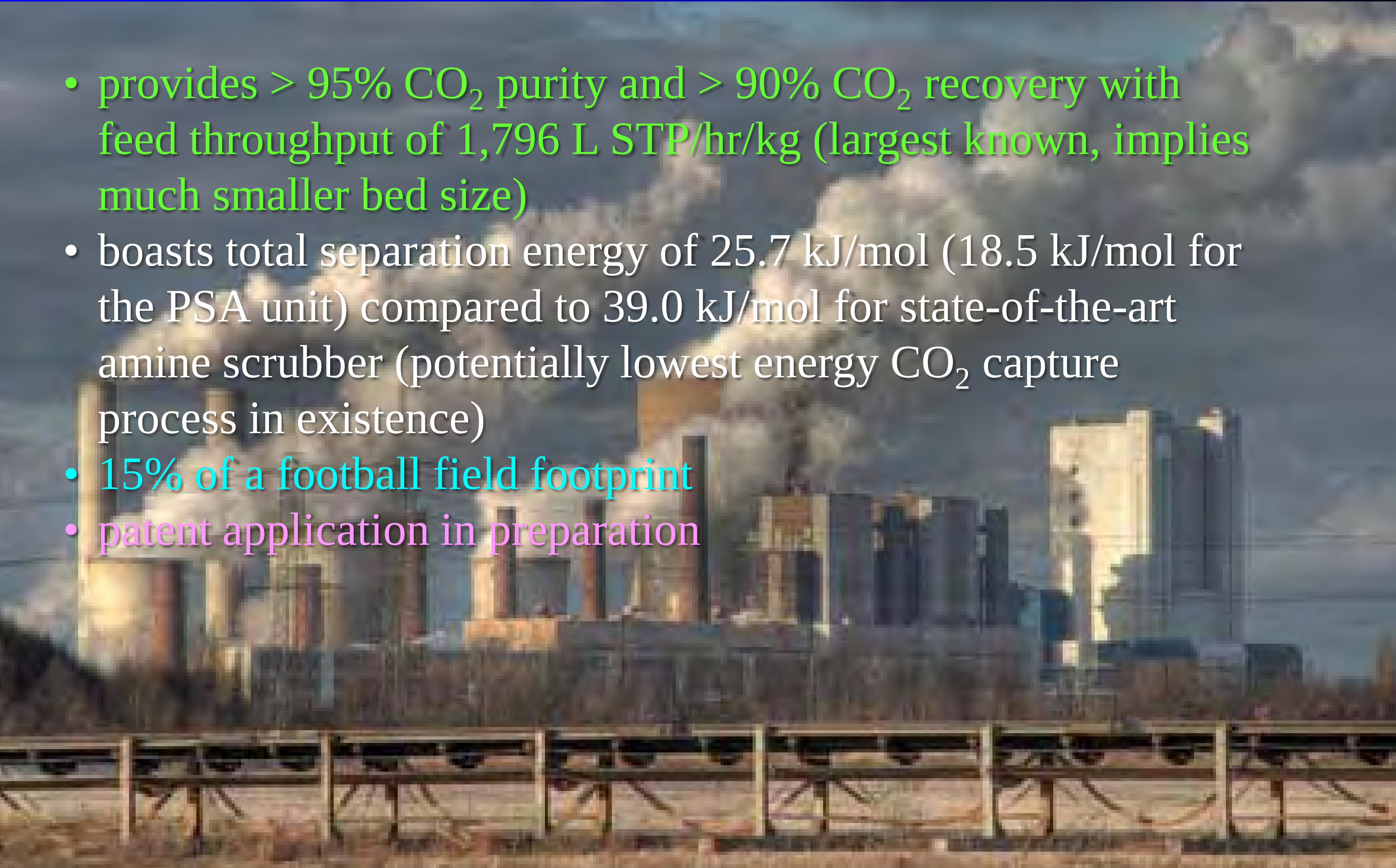



Where are we now?

PSA Process and Flowsheet Development

Low Energy PSA Process for CO_2 Capture Invented using Validated PSA Process Simulator

- provides > 95% CO_2 purity and > 90% CO_2 recovery with feed throughput of 1,796 L STP/hr/kg (largest known, implies much smaller bed size)
- boasts total separation energy of 25.7 kJ/mol (18.5 kJ/mol for the PSA unit) compared to 39.0 kJ/mol for state-of-the-art amine scrubber (potentially lowest energy CO_2 capture process in existence)
- 15% of a football field footprint
- patent application in preparation



Amine Scrubbing vs PSA

- amine scrubbing has solvent stability issues; adds to solvent regeneration costs and sludge waste stream; adsorbent stability not an issue, with 5 to 10 yr lifetime typical in PSA
- amine scrubbing suffers from corrosion issues – leads to expensive materials of construction; corrosion not an issue in PSA, with vacuum swing operation not requiring high pressure vessels
- amine scrubbing not yet sulfur (SO_2) tolerant; PSA/flowsheet SO_2, NO_x and H_2O tolerant – traces may end up in CO_2 product
- amine scrubbing needs steam source for CO_2/amine bond breakage, and to increase stripper temperature and possibly pressure; significant infrastructure and capital costs for plumbing and heat exchangers; PSA needs only electricity and a vacuum pump/blower for adsorbent regeneration – does not affect power plant operations
- amine scrubbing needs a water source for Na_2CO_3 addition and as stripping vapor; PSA has no need for water
- amine scrubbing prefers lower CO_2 feed concentrations; PSA handles wide range of CO_2 feed concentrations

Low Energy Pressure Swing Adsorption (PSA) Process for CO_2 Capture from Flue Gas

Energy Consumption Breakdown

Throughput = 898 L_{STP}/kg/h

Unit	Consumption (MW)	Parasitic Loss (%)	kJ/mol CO_2 Removed	kWh/ton CO_2 Removed
Blower	19.73	3.95	7.13	45.01
PSA Compressor	48.70	9.74	17.60	111.11
Pipeline Compressor and Liquefaction	40.60	8.12	14.67	92.63
Total	109.03	21.81	39.40	248.76

Possibly the most affordable, energy efficient, and easily implemented and operated CO_2 capture process developed to date.

Low Energy Pressure Swing Adsorption (PSA) Process for CO_2 Capture from Flue Gas

Energy Consumption Breakdown

Throughput = 1796 L_{STP}/kg/h

Unit	Consumption (MW)	Parasitic Loss (%)	kJ/mol CO_2 Removed	kWh/ton CO_2 Removed
Blower	19.73	3.95	7.13	45.01
PSA Compressor	51.27	10.25	18.53	116.98
Pipeline Compressor and Liquefaction	40.60	8.12	14.67	92.63
Total	111.60	22.32	40.33	254.62

More expensive than the previous lower throughput PSA process, but with columns less then half the size – effect of cycle time can be significant!


Where are we going?

Scale of PSA System for CO_2 Capture from 500 MW Power Plant

Is it possible to achieve a 1/10th volume reduction?

- increase working capacity 10 fold (herculean)
- operate at 1/10th cycle time (achievable)
- known as rapid PSA

although rapid PSA offers potential for a low-cost solution for CO_2 capture, the extent of size reduction achievable is, at the moment, unknown

QuestAir H-6200 Rapid PSA-Installed at ExxonMobil Facility

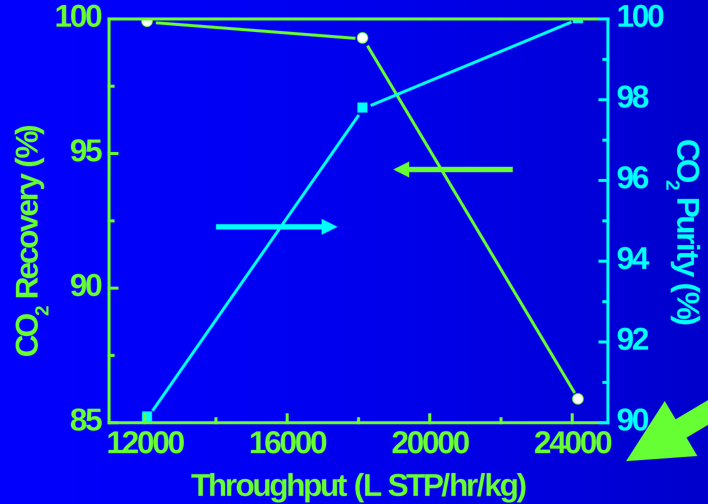
H_2 Production Rapid PSA
~ 12,000 Nm^3/h/module

H_2 Production
Conventional PSA
~ 20,000 Nm^3/h

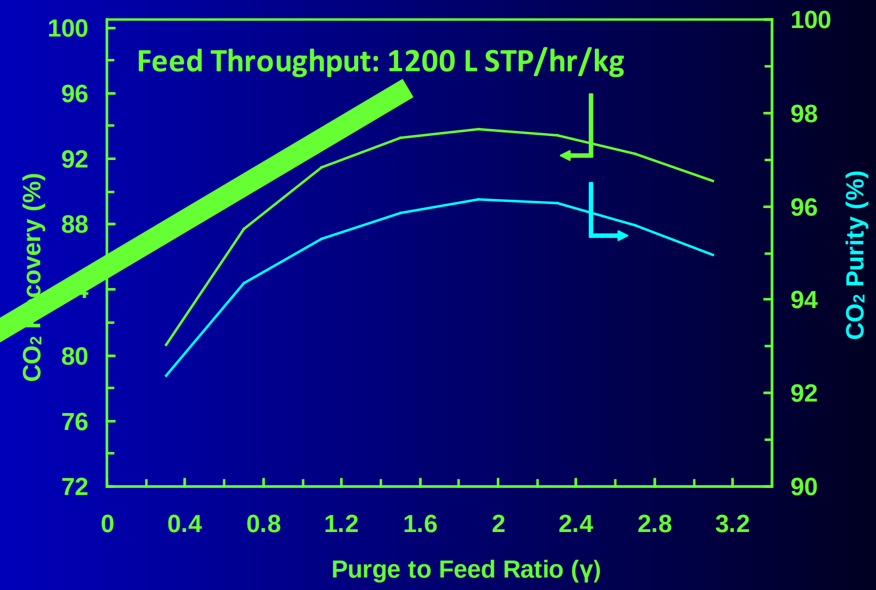
Two of Questair's modules do 20% better than this 6-bed PSA system and are much smaller.

CO_2 Capture: Comparison of Rapid PSA to Conventional PSA

Rapid PSA*



Conventional PSA*



Notice the order of magnitude increase in feed throughput for the rapid PSA system under similar conditions using 13X zeolite.

Issues: pressure drop, adsorbent attrition and mass transfer

* Results obtained from a experimentally validated Dynamic Adsorption Process Simulator (DAPS).

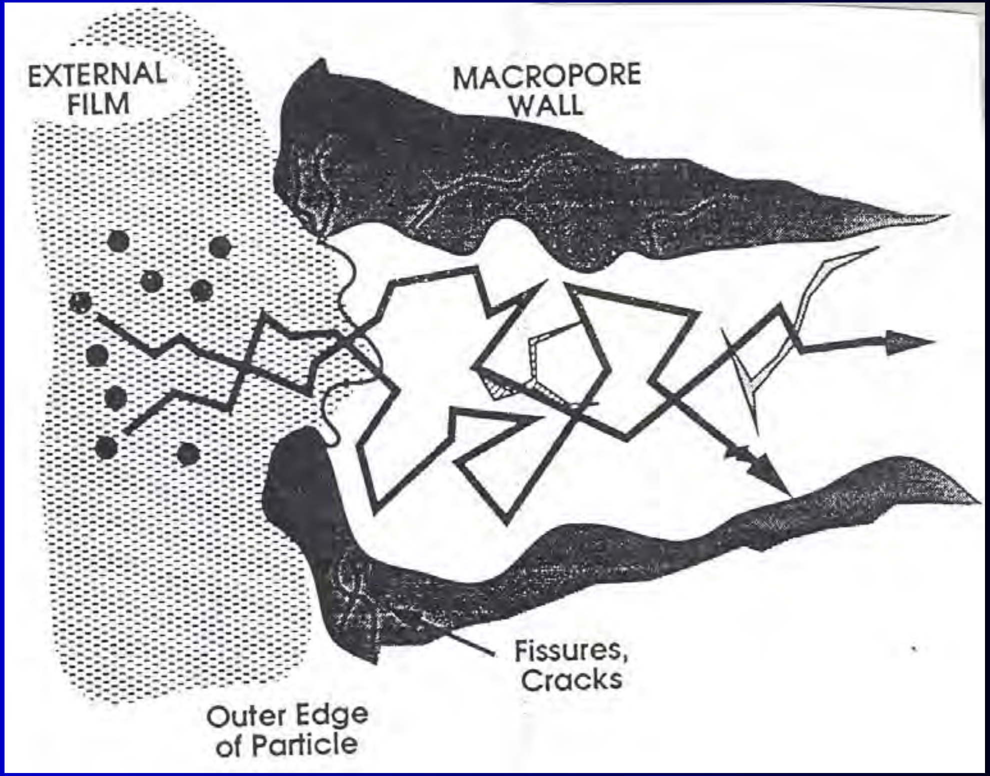
Mass Transfer Resistances in Adsorption Systems

Goal of Practical Adsorbent

Concentrate a large amount of solid surface area in as small a volume as possible, while still satisfying process constraints.

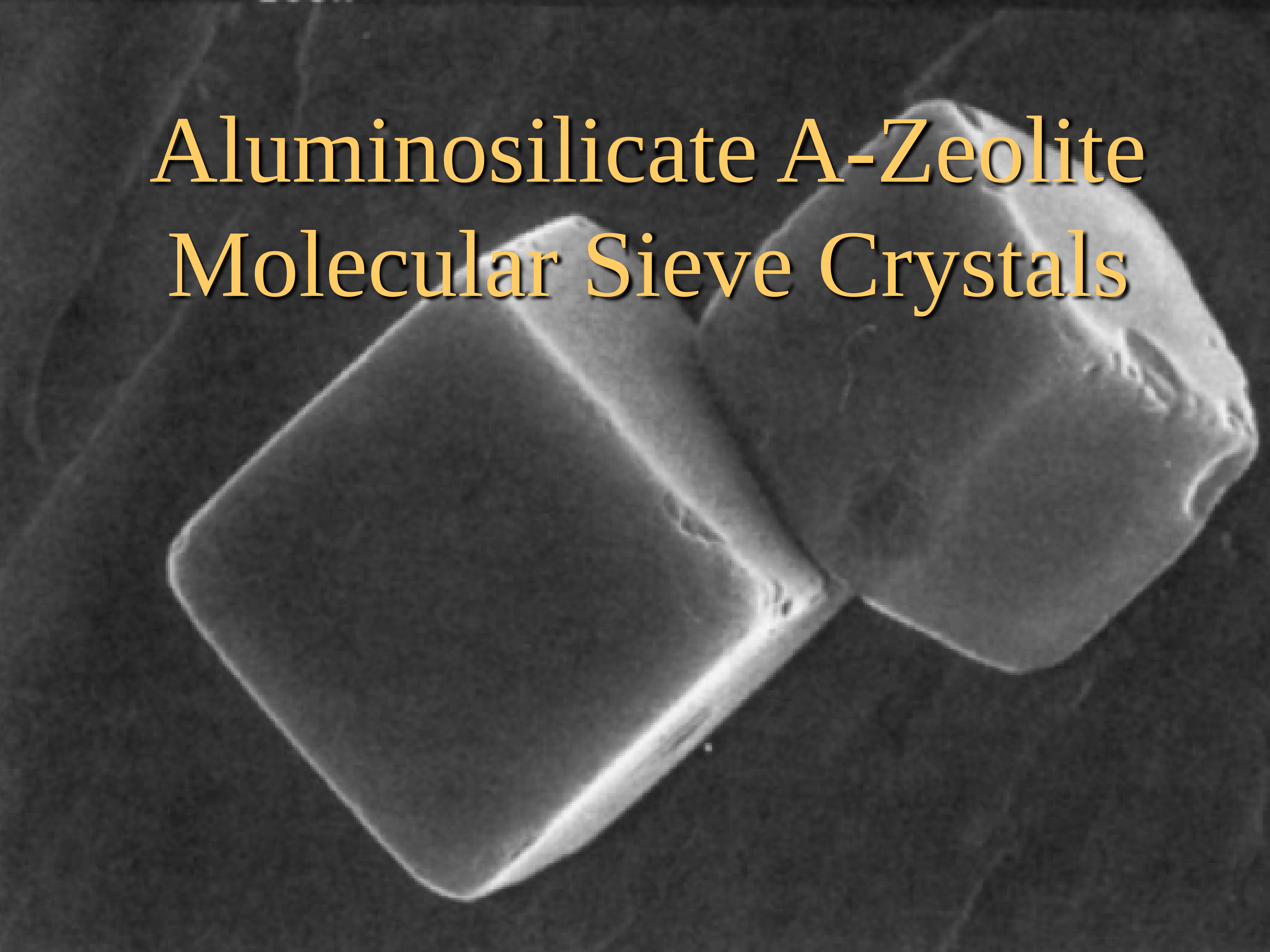
Leads to Resistances

- external film
- macropore
- micropore



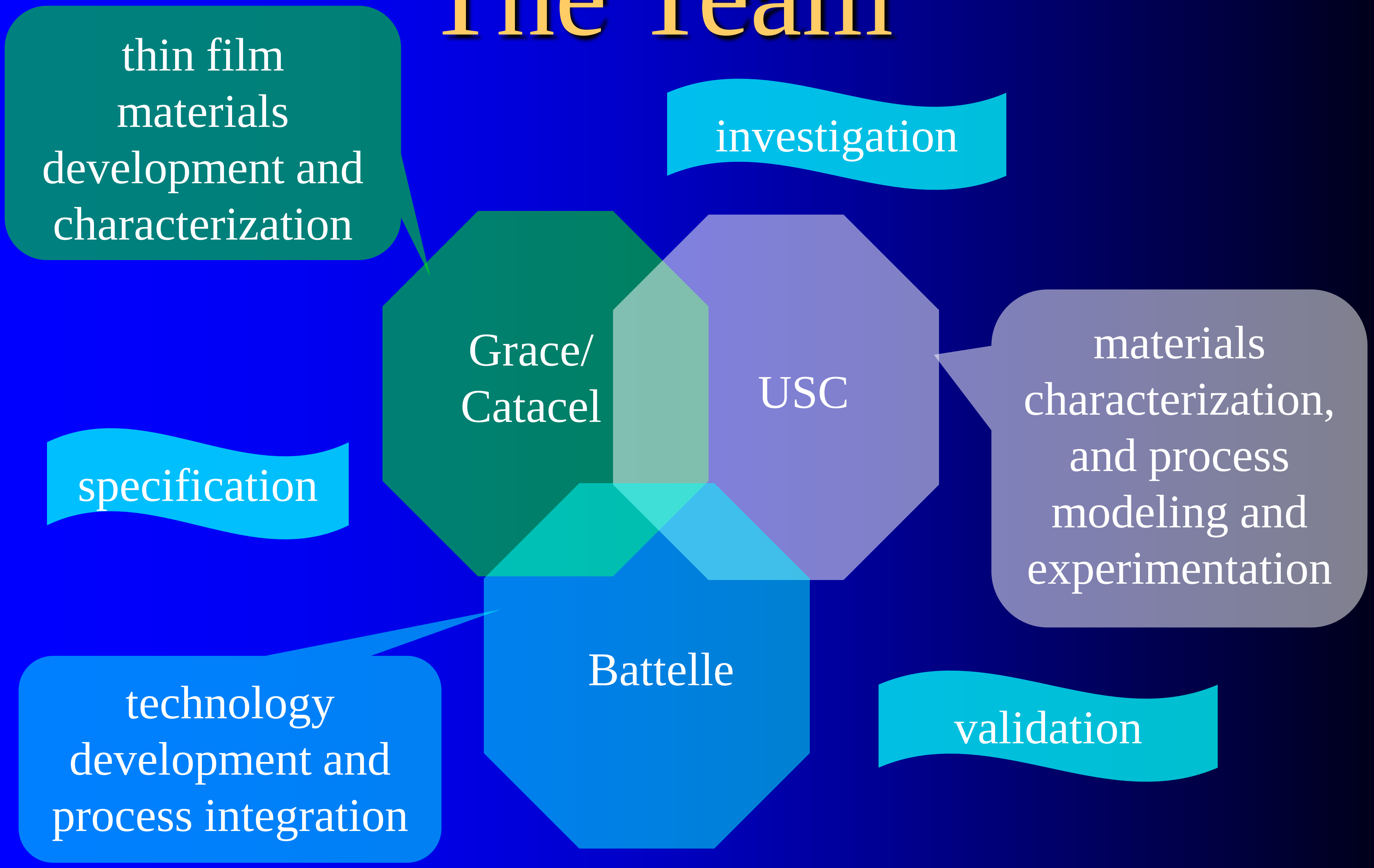
powders, beads, pellets, extrudates, granules

Aluminosilicate A-Zeolite Molecular Sieve Crystals



Aluminosilicate Zeolite Molecular Sieve Pellets

The Team


thin film materials development and characterization
investigation
Grace/ Catacel
USC
materials characterization, and process modeling and experimentation
specification
Battelle
validation
technology development and process integration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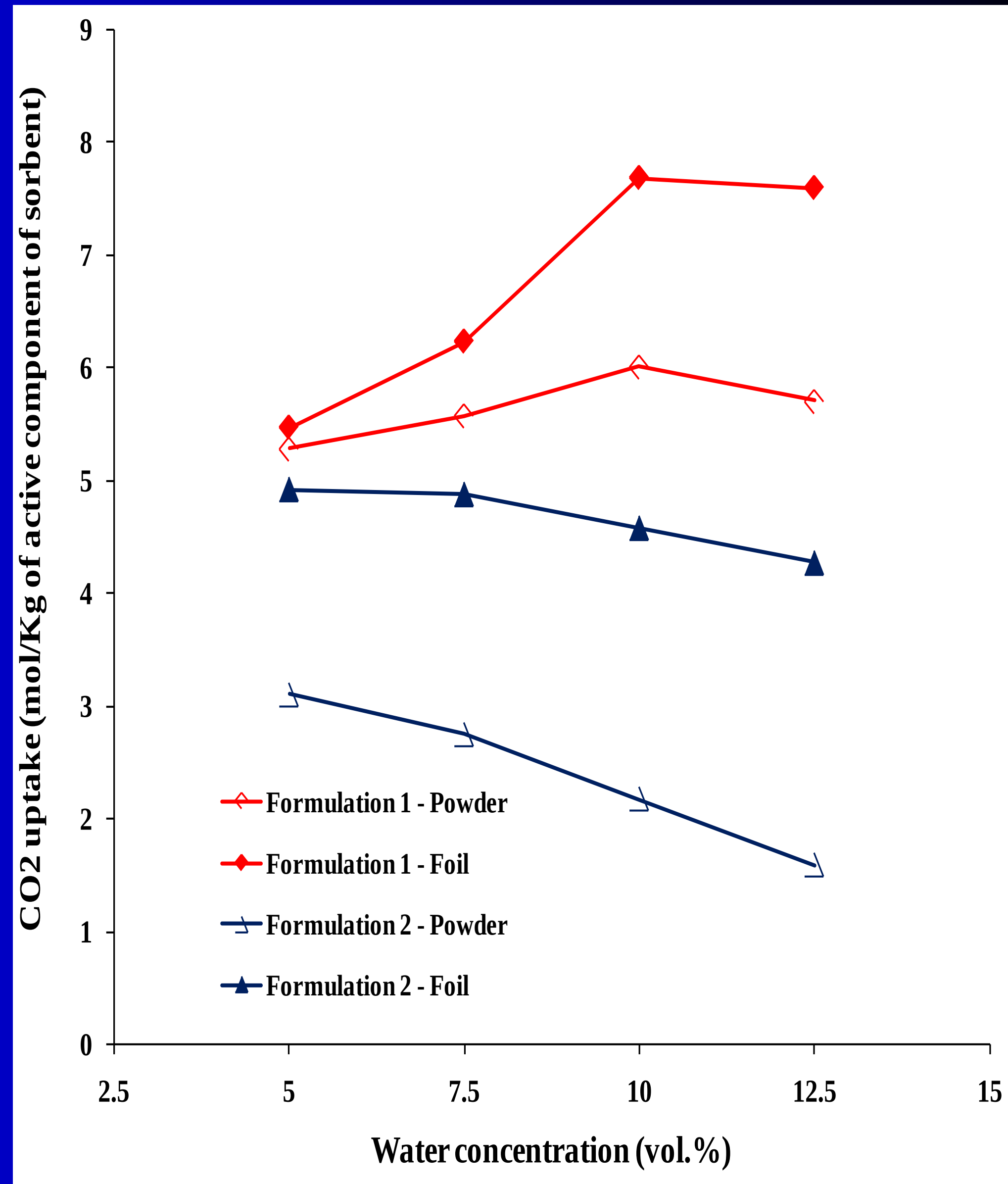
Coated Thin Metal Foil

Catacel Structured Sorbent Experience

- Catacel has prepared a structured bed comprised of thin metal foil coated with sorbent material to demonstrated proof of concept for CO_2 capture in work with Youngstown State University
- It was found that two different sorbent formulations coated on foil exhibited enhanced sorption capacity relative to sorbent in powder form

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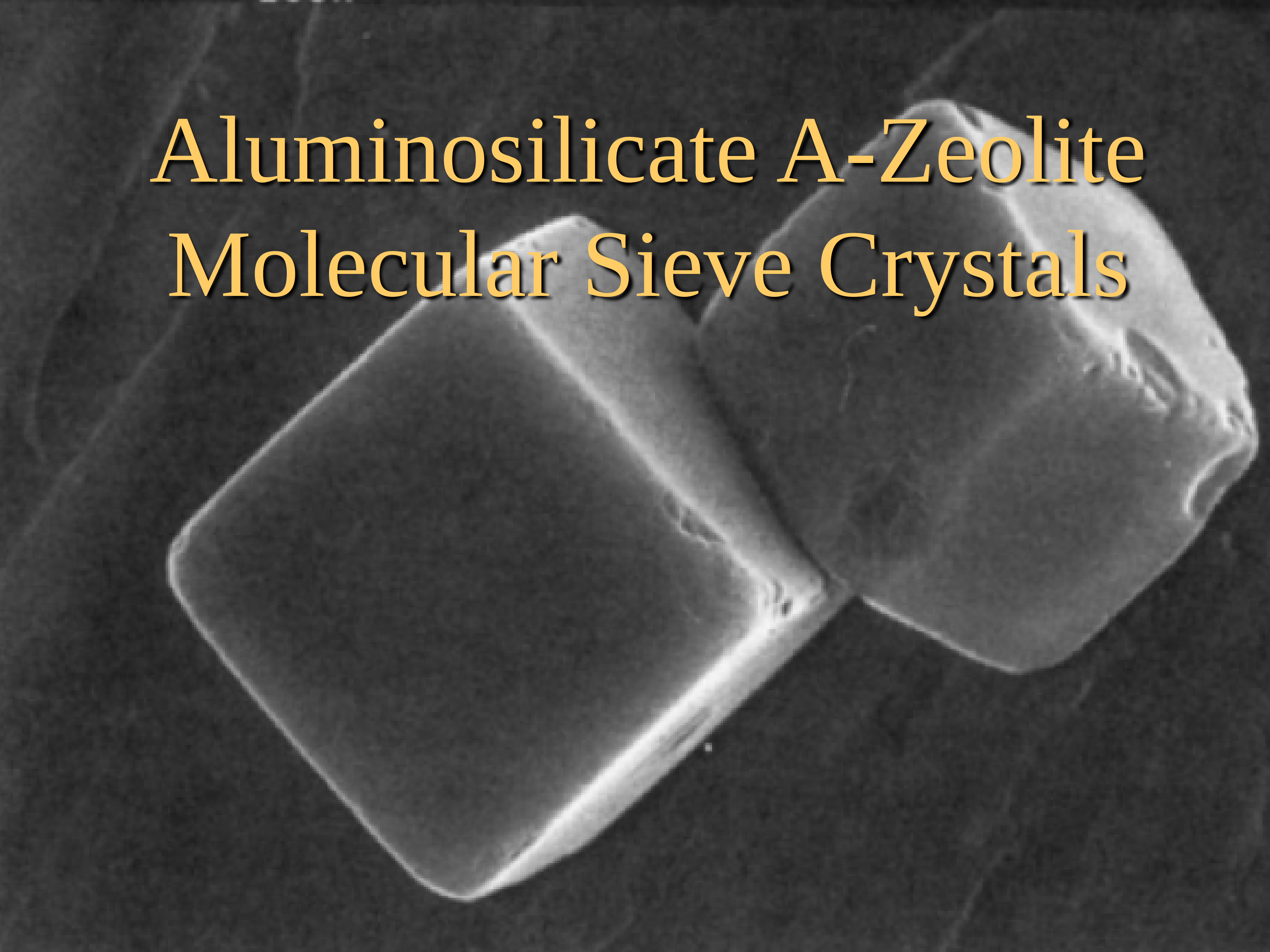
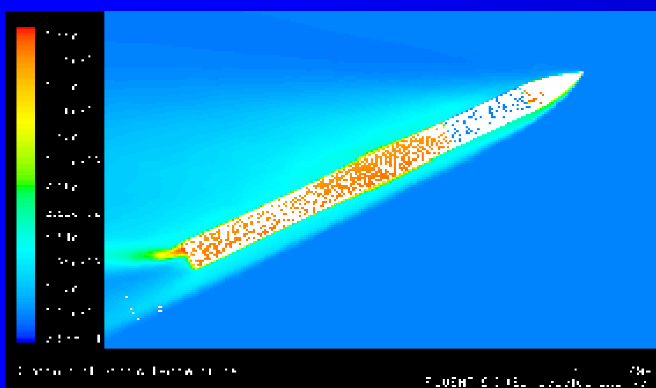


Aluminosilicate Zeolite Molecular Sieve Pellets


Battelle
The Business of Innovation

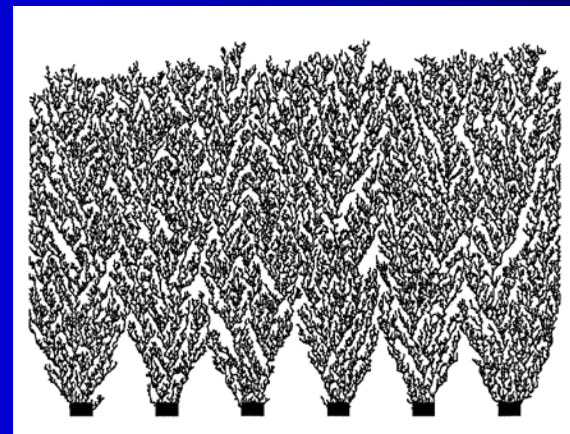
Multi-Disciplinary Modeling for Conceptual Design, Optimization and Control

Battelle has a long history of creating custom models that combine multi-disciplinary phenomena.



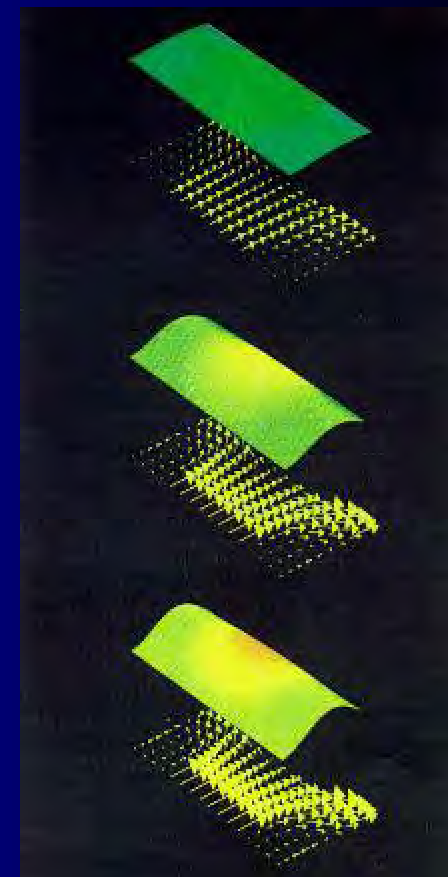
Missile re-entry physics

New : CFD to improve structured adsorbents



Plugging of a missile thruster control valve

Gas dynamics and crack propagation in running fracture



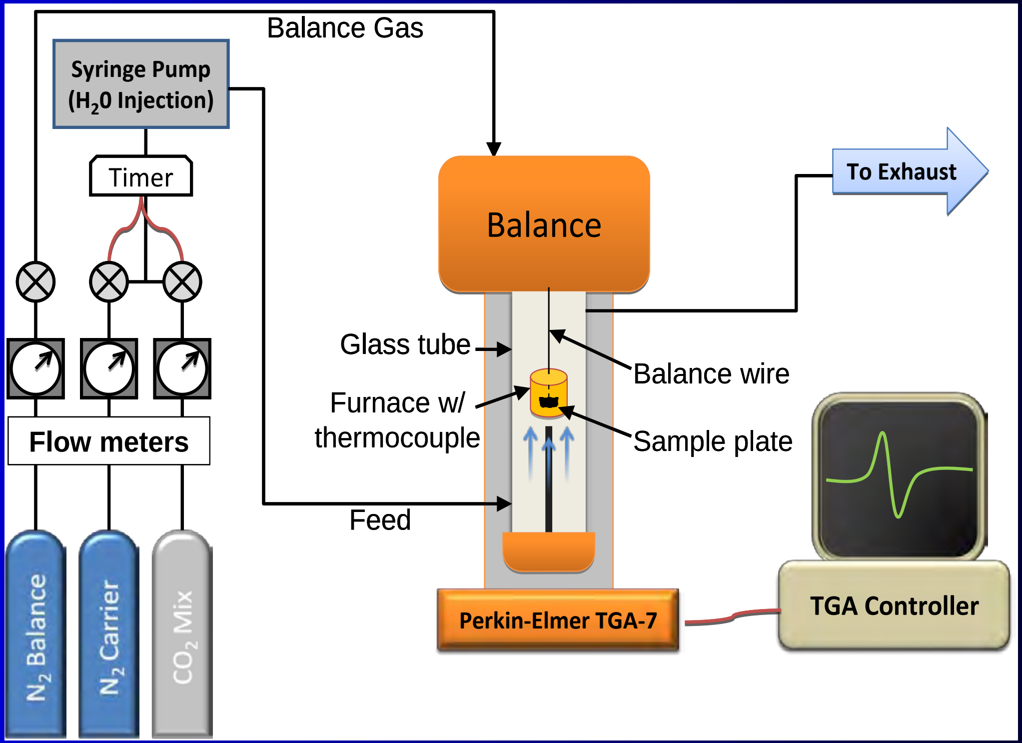
Fluid-structure interaction


UNIVERSITY OF
SOUTH CAROLINA
1801

Rapid Adsorbent Characterization

NETL's Solid Amine

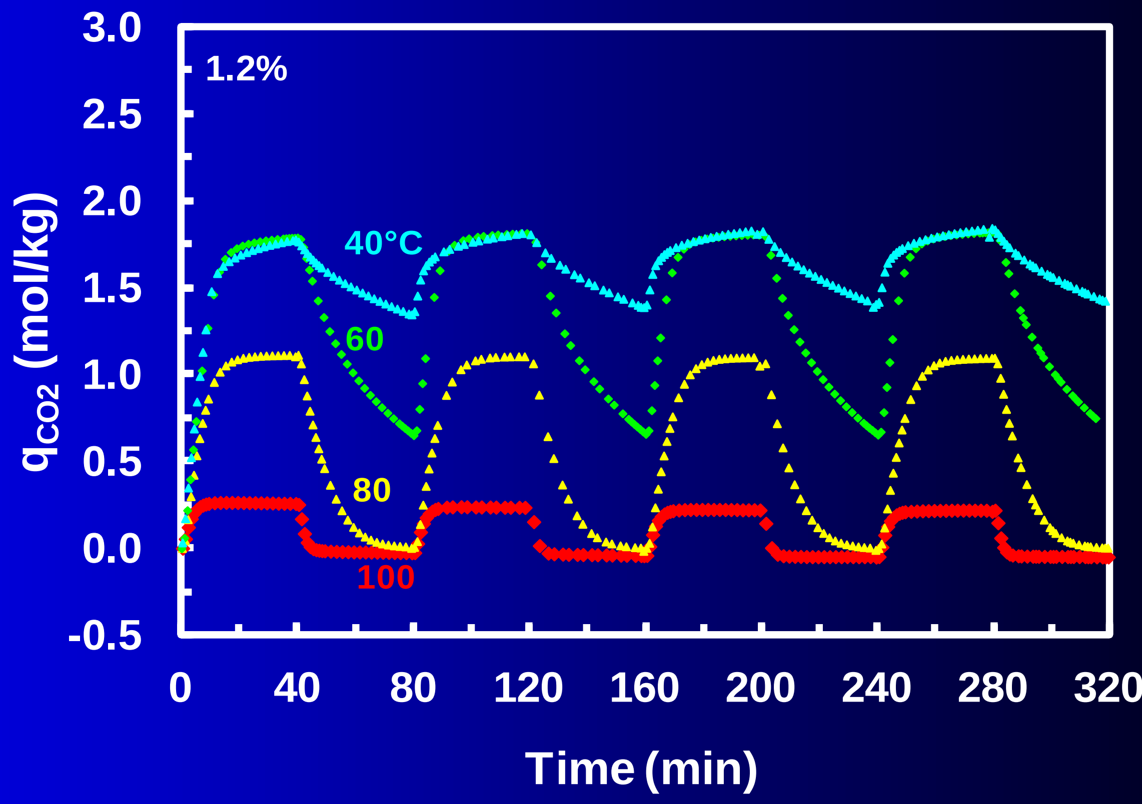
- G10 sample (~20 mg)
  - activation at 100°C for 80 min in N_2
  - cycling at 40, 60, 80, and 100°C
    - 40 min. adsorption in CO_2-N_2 mixture
    - 40 min. desorption in 100% N_2
  - %CO_2 w/P_T=1 atm
    - 100%
    - 88.6%
    - 69.8%
    - 56.1%
    - 32.5%
    - 14.5%
    - 4.8%
    - 1.2%



A. D. Ebner, et al., Ind. Eng. Chem. Res (2011).

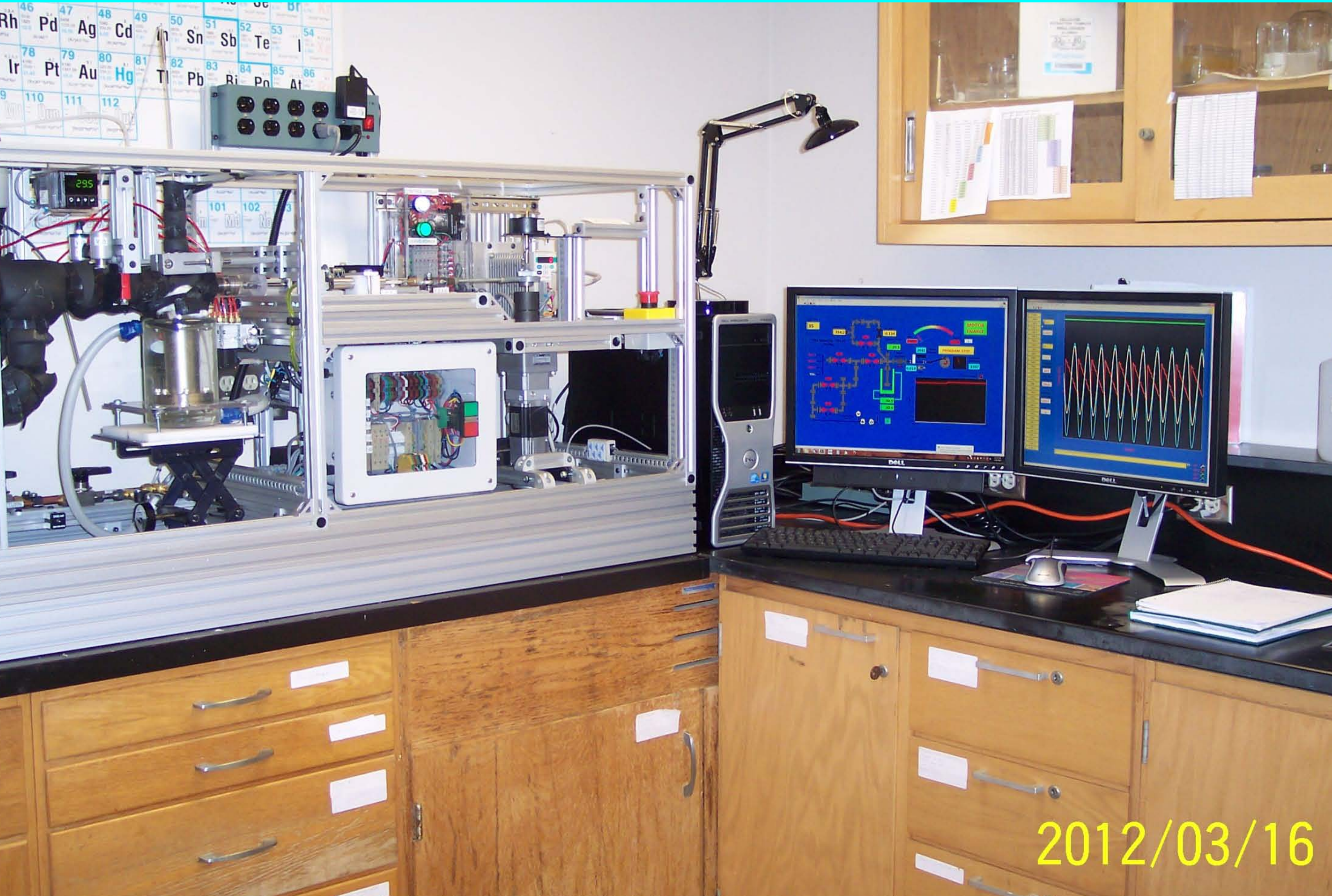
Typical Cycling Results for 1.2% CO_2

- loading reaches equilibrium at 100°C and 80°C but not at 40°C and 60°C
- fast initial uptake followed by a slow uptake of CO_2, more apparent at 40 and 60°C
- multistep adsorption/ reaction mechanism is taking place
- thermodynamic limitation at higher temperatures
- kinetic limitation at lower temperatures



A. D. Ebner, et al., Ind. Eng. Chem. Res (2011).

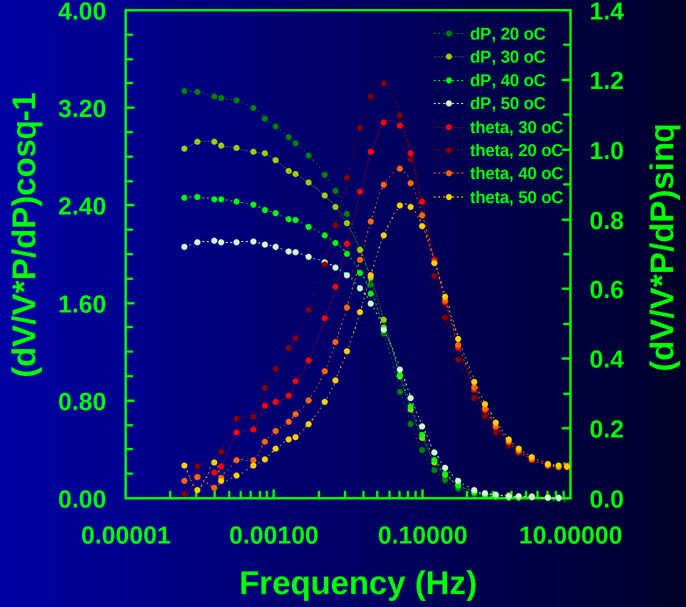
Volumetric Frequency Response Apparatus

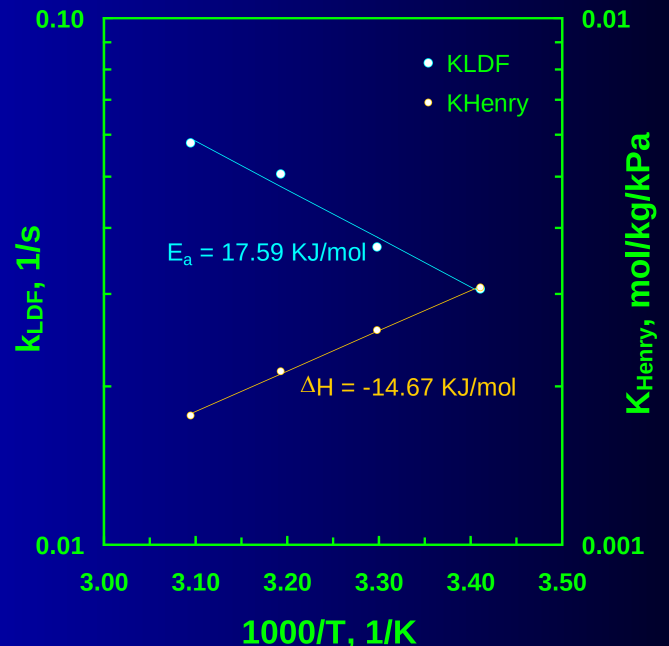


Dynamic Characterization of Adsorbents via Volumetric Frequency Response

- For LDF coeff. determination and understanding of transport processes in adsorbents
- 0 – 1atm; 10 – 60 °C
- Comsol multipore transport process model for fitting.

O_2 on Shirasagi CMS 172 3K





1-Bed Rapid PSA System

Complex PSA Cycle Schedule Analysis

Construction Almost Complete

5-Bed CO_2 Capture PSA System

Under Construction

Suitable for Power Plant Demonstration

How are we going to get there?

Specific Objectives

In addition to demonstrating at the bench-scale that a rapid PSA system is able to achieve the target of less than 35% increase in the cost of electricity, we will also

- develop a low cost, structured adsorbent with low pressure drop, high mass transfer rates, high capacity for CO_2 and high availability that will enable large feed throughputs, and
- further develop and refine PSA cycles to match the performance of the new structured adsorbent to reduce the power duty of the product/recycle compressor

These objectives will be accomplished using a suite of bench-scale experimental systems and sophisticated modeling tools.

Task 2: Period I

Task 2.0: Baseline Adsorbent Tests		10/11	05/12
2.1	Provide standard sorbents	10/11	10/11
2.2	Slurry coating tests	10/11	11/11
2.3	Coating Evaluation	11/11	12/11
	Candidate Baseline Structure Identified	12/11	12/11
2.4	Thermogravimetric Analysis Studies	10/11	01/12
2.5	Kinetic Studies	01/12	04/12
2.6	Thermodynamic Studies	01/12	04/12
2.7	Single Column rPSA Unit Construction	10/11	01/12
2.8	Single Column rPSA 2-Step Cycling	01/12	02/12
2.9	Single Column rPSA Multi-Step Cycling	02/12	05/12
2.10	Contamination Experiments	01/12	03/12
	Baseline Adsorbent Structure Selected	05/12	05/12

Task 3: Periods I, II and III

Task 3.0: 3D Structure Improvements		05/12	05/14
3.1	Provide Standard Sorbents	05/12	06/12
3.2	Develop Prototype Model	05/12	06/12
3.3	Develop Baseline Model	06/12	07/12
3.4	Develop Constraint Matrix for Model	05/12	06/12
3.5	Optimize Structure Solution	05/12	09/12
	Optimized Structures Identified	09/12	09/12
3.6	Manufacture of Optimized Structure	10/12	12/12
3.7	Pressure Drop Test Bed Construction	05/12	09/12
3.8	Pressure Drop Test Bed Experiments	12/12	02/13
3.9	Baseline Model Validation and Sim.	03/13	05/13
3.10	Pressure Drop Validations	05/13	10/13
	Pressure Drop Correlations Validated	10/13	10/13
3.11	Pressure Drop Correlations	11/13	05/14

Task 4: Periods I, II and III

Task 4.0: Process Modeling		04/12	06/14
4.1	DAPS Valid. & Calibr. Baseline Ads.	04/12	07/12
4.2	Rapid PSA Process Modeling	04/12	10/12
4.3	rPSA Modeling w/Model Adsorbent	10/12	04/13
4.4	rPSA Modeling w/Improved Adsorbent	04/13	10/13
4.5	rPSA Modeling w/Develop Adsorbent	10/13	04/14
	Process Modeling Completed	06/14	06/14

Task 5: Periods I and II

Task 5.0: Zeolite Improvements		05/12	02/13
5.1	Review of experimental data	05/12	06/12
5.2	Ranking of issues to goals	06/12	07/12
5.3	Preparation of Incremental Samples	07/12	09/12
	Sample preparation complete	09/12	09/12
5.4	Sample Evaluation and Validation	10/12	02/13
	Improved Zeolite Selected	02/13	02/13

Task 6: Periods I, II and III

Task 6.0: Rapid Adsorption Test Bed		04/12	04/14
6.1	Supply Adsorbents	04/12	05/12
6.2	Multi Column rPSA Construction (1)	04/12	09/12
	Initial Construction Ready	09/12	09/12
	Decision to Proceed with Period 2	09/12	09/12
6.3	Multi Column rPSA Construction (2)	10/12	04/13
6.4	Baseline Core Preparation	05/12	07/12
6.5	Best 3D Structure Preparation	03/13	04/13
6.6	Low Cost Structure Preparation	11/13	01/14
6.7	Multi Col. rPSA Testing w/Baseline	04/13	10/13
6.8	Multi Col. rPSA Testing w/Developed	11/13	04/14
	Multi Bed Test Completed	04/14	04/14

Task 7 : Periods II and III

Task 7.0: Low Cost Structure Development		10/12	10/13
7.1	Supply Adsorbents	10/12	10/12
7.2	Investigation of New Support Materials	10/12	02/13
7.3	Investigation of New Mfg Processes	10/12	02/13
7.4	Manufacture of New Structures	02/13	05/13
7.5	Sample Evaluation and Validation	05/13	09/13
	Low Cost Structure Selected	09/13	09/13
	Decision to Proceed with Period 3	09/13	09/13

Task 8: Period III

Task 8.0 Scale-Up Economics		06/14	09/14
8.1	Final Process Heat & Mass Balance	06/14	07/14
8.2	Process Flow Diagram	07/14	07/14
8.3	Compression Equipment Costing	07/14	09/14
8.4	Plant Operating Costs	07/14	09/14
	Process Plant Economics Completed	09/14	09/14
	Development and Testing Completed	09/14	09/14

Deliverables at End of Each Budget Period

Budget Period 1: Proof-of-concept that zeolite crystals can be coated onto a basic metal structure; 1-bed RPSA and pressure drop (PD) experimental systems constructed; refinements of PSA cycle and process flow sheet toward meeting 35% limit of COE increase; selection of commercial zeolite adsorbent to focus on

Budget Period 2: Improved coated metal structure in terms of cost and performance, based on CFD simulations and PD experiments; RPSA proof-of-concept based on 1-bed RPSA experiments and modeling; 5-bed RPSA experimental system construction initiated.

Budget Period 3: Optimized coated metal structure; RPSA proof-of-concept based on 5-bed RPSA experiments and modeling; final refinements in RPSA cycle and process flow sheet; complete flow sheet analysis, scale-up, comparison against targets, and preliminary pilot-scale design.

Budget

Project Team Member	Budget Period 1 10/2011 – 9/2012		Budget Period 2 10/2012 – 9/2013		Budget Period 3 10/2013 – 9/2014		Total
	Gov. Share	Cost Share	Gov. Share	Cost Share	Gov. Share	Cost Share	
Grace	139441	34860	75084	18772	145089	36272	449518
USC	670000	167500	490000	122500	490000	122500	2062500
Battelle	239115	59978	191791	47930	159744	39998	738556
Catacel	125592	31398	172187	43047	100662	25166	498052
TOTAL	1174148	293736	929062	232249	895495	223936	3748626

Breakdown in % of Total Budget

USC	55.0%
Battelle	19.7%
Catacel	13.3%
Grace	12.0%

Conclusions

- commercial zeolite showing much promise as effective adsorbent for CO_2 capture from flue gas
- 1-bed PSA experiments showing possibility to achieve 95% CO_2 purity and 90% CO_2 recovery
- validated DAPS showing PSA energy requirements better than amine scrubbing
- rapid PSA showing potential to significantly reduce PSA column size and thus plant footprint

A major outcome of this work will be proof-of-concept at the bench-scale and the RPSA process design utilizing a structured adsorbent and flowsheet that will enable the successful design and development of a pilot-scale demonstration.

Acknowledgements

Funding provided by

SAGE, and

DOE/NETL

is greatly appreciated!

Thank You!

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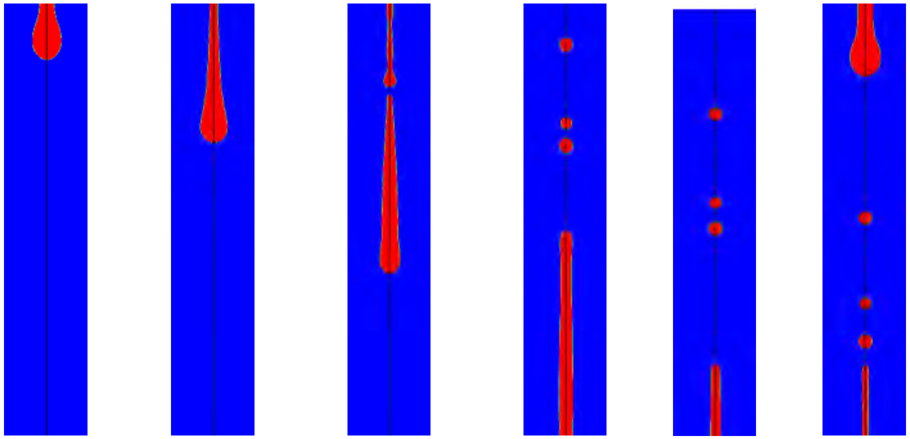
Coated Metal Foil Structured Adsorbents

- **PSA systems operate at elevated throughputs and bed velocities**
- **Conventional packed bed systems have deficiencies in areas critical to the performance of a rapid PSA system including:**
  - High pressure drop
  - Mass transfer limitations
  - Adsorbent attrition
- **Coated structured adsorbents provide significant advantages over packed beds in critical performance areas including:**
  - Low pressure drop
  - Improved mass transfer
  - Attrition resistant
- **Utilization of bed structures that facilitate the flow along the bed is critical to the development of PSA systems that operate at elevated throughputs and space velocities**

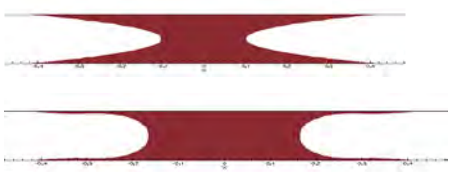
- Catacel is the world expert in commercial applications involving catalyst-coated (metal oxide) metal foils and foil structures, with over 25 years of experience. Catacel reactive heat exchangers have been successfully used for hydrogen production for over 4 years under much more demanding conditions (e.g. 800 C) than will be encountered in a rapid PSA process.

Battelle's Experience in Modeling of Fluid Layers

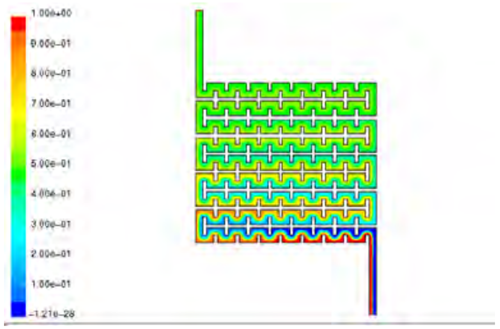
- Several commercial codes are available that accurately model thin layer and capillary behavior.
- Battelle has modeled and designed these systems for applications in material processing, medical devices, and industrial processes.



Liquid breakup on a thin wire to enhance mass transfer of gas into liquid. US Patent 6,582,498



Evolution of a drop with sudden contact between two plates



Flow in a lab-on-a-chip device

High Temperature Micro-Channel Reactor

- Goal: Predict steady-state, global temperature profiles for use in thermal stress analysis and performance life prediction. These micro-channel systems have hundreds to thousands of channels.
- Developed rapidly-executing custom models for conceptual designs and global calculations. Agreed well with detailed calculations (see comparison of Fluent and NetQ).
- Developed efficient meshing algorithms to enable use of commercial software for high resolution calculations.
- Reduced design cycle from months to weeks.