MONASH University

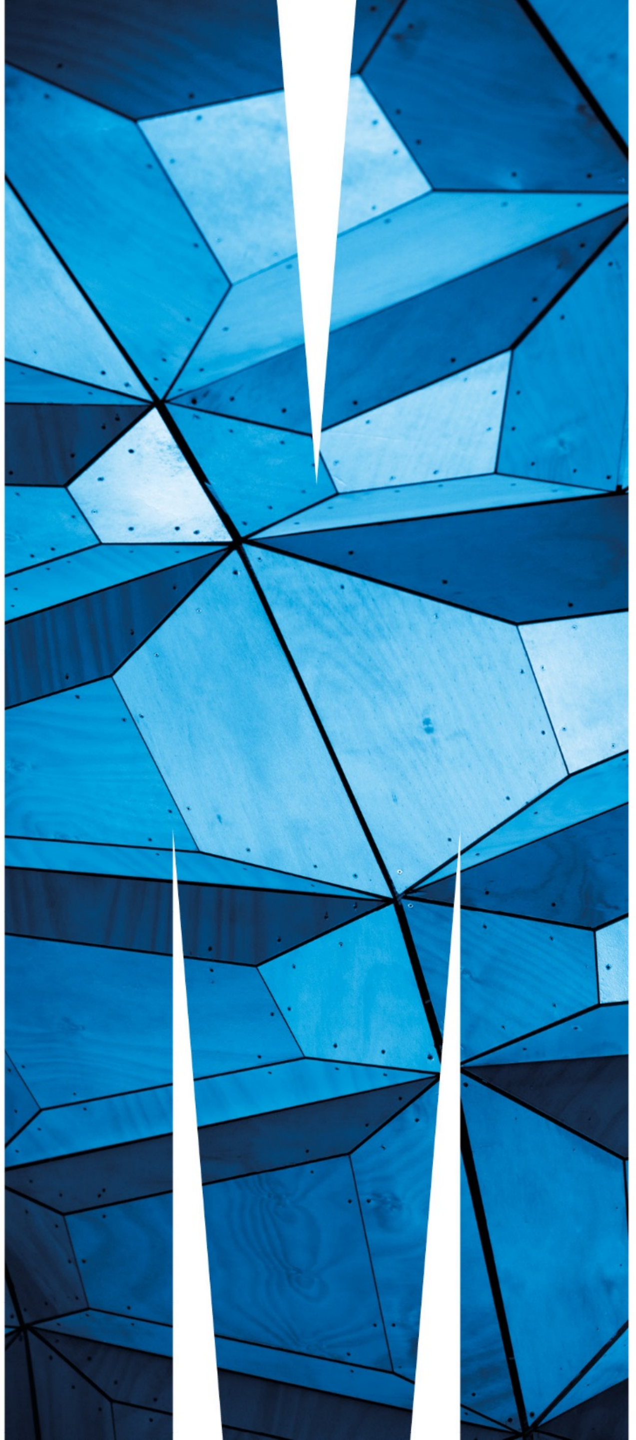
Emerging Tends in Adsorption Based CO_2 Capture

Alan L Chaffee

School of Chemistry, Monash University

GROUP OF EIGHT AUSTRALIA

Hypercap, Oslo, Sept 13, 2017



Outline

- What for?
  - Sequestration
  - Enhanced Oil Recovery
  - Food grade
  - Greenhouse use
  - Chemical products
  - Hydrocarbon fuels
- What from?
  - Flue gas (coal or other)
  - Natural gas
  - Biofuel
  - Industry processes (cement)
  - Air
- What material?
  - Carbons
  - Zeolites
  - MOFs
  - Amines (composites)
  - Oxides
- What approach?
  - PSA
  - VSA
  - TSA
  - ESA
  - Hybrid approaches

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  - TSA
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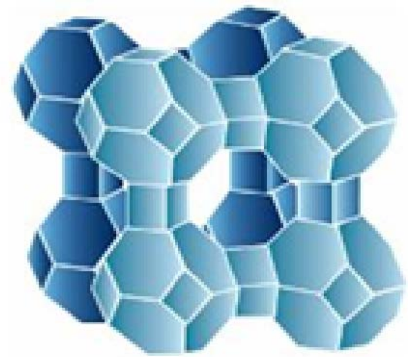
Product

Problem

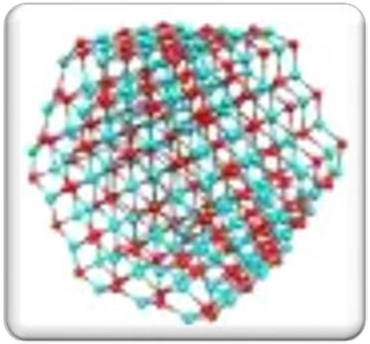
Performance

Productivity

Adsorbent Materials

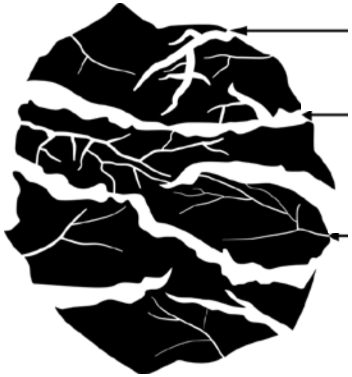


Zeolites



Metal Oxides

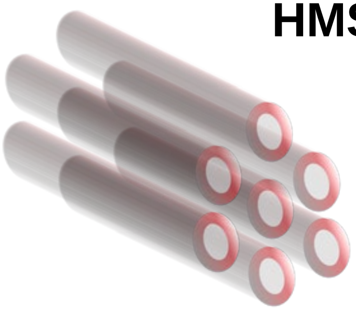
Metal Organic Frameworks (MOFs)



Carbons

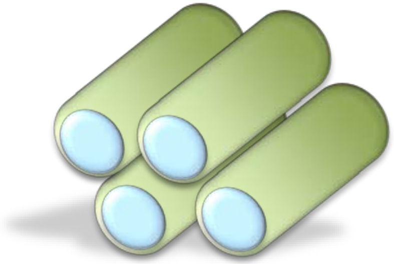
Composites: mesoporous supports incorporating amines

HMS



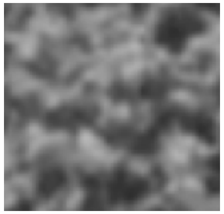
Pore Vol ~ 0.7 mL/g

SBA-15



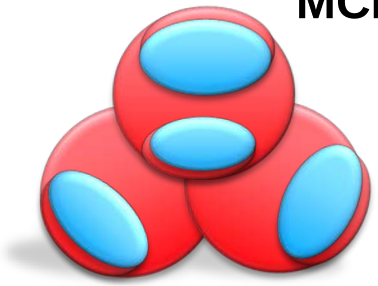
Pore Vol ~ 1.0 mL/g

KIL-2



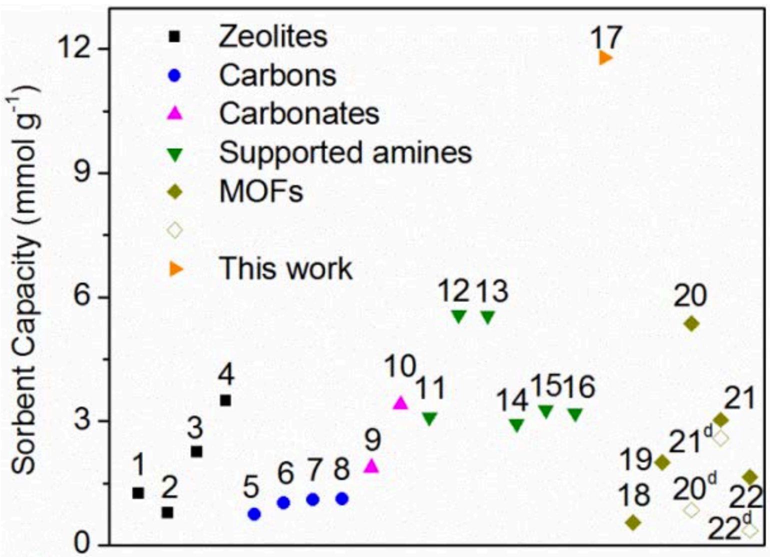
Pore Vol ~ 1.6 mL/g

MCF



Pore Vol ~ 2.8 mL/g

Summary Comparison



Num.	Sorbent	CO_2 partial pressure kPa	Humidity %	Temperature Adsorp. °C	Temperature Desorp. (activation) °C	Sorbent capacity mmol g^{-1}	Ref.
	Zeolites						
1	Nature zeolite	15	100[b]	25	115	1.25	4
2	Zeolite 4A	15	100[b]	25	115	0.79	4
3	Zeolite 13X	6[a]	0	25	(320)	2.25	5
4	Zeolite LiLSX	6	1.3-12.6[a]	35	(>300)	~0.2-3.5	6
	Carbons						
5	Activated carbon	10[a]	0	25	(150)	~0.75	7
6	N-doped carbon	10[a]	0	25	(150)	1.01	7
7	SWCNT	10[a]	0	35	NA	~1.1	8
8	MWCNT	15	7[a]	60	120	1.12	9
	Alkali carbonates						
9	Supported K_2CO_3	15	15[a]	55	(200)	1.88	10
10	Supported Na_2CO_3	14.4	10[a]	50	120	~3.4	11
	Supported amines						
11	MCM-41/PEI	15	13.1[a]	75	100	~3.1	12
12	MC400/10PEI%83	10	1.6[a]	75	100	5.58	13
13	HAS	10	1.6[a]	25	130	5.55	14
14	PE-MCM41/tri	5	27[b]	25	100	2.94	15
15	PE-MCM41/mono	5	74[b]	25	(200)	3.27	16
16	Poly(TMSEN)	10	18[b]	25	100	3.20	17
17	Silica foam/PEI	8	18[b]	25	100	11.8	This work
	Metal-organic frameworks (MOFs)						
18	Cu/BTC	10	9[b]	25	(170)	~0.50	18
19	Ni/DOBDC	10	9[b]	25	(150)	~2.0	18
20	Mg/DOBDC	10	0	38	(250)	4.93	19
						2.41[c]	
		16.9	0	25		5.36	20
			70[b]			0.85[d]	
21	Co/DOBDC	16.9	0	25	(250)	3.03	20
			70[b]			2.59[d]	
22	Zn/DOBDC	16.9	0	25	(270)	1.65	20
			70[b]			0.36[d]	

Qi et al, Nat. Commun. 2014, 5, 5796

Materials – multitude of variations

Chmisorbents vs. Physisorbents

Carbons	Microporous, mesoporous, nanoporous, graphitic, … Templated, MWNT, SWNT, carbon fibres, …. C-molecular sieves, N-doped,…
Zeolites	Type X, Y, A, MOR, CHA, HZMS5, H-form, Na-form, Ca-form, Mg-form,….. Molecular sieves
MOFs	MOFs, ZIFS, COFs,… HKUST, DMOF, UiO-66, UTSA, MIL-101, IRMOF-8,…. Zn-DABCO, Co-DABCO, Mg/DOBDC, ZNBuBPDC, …. mmem-MOFs, IRMOF-8-NO2,….
Amine composites	PEI, TEPA, linear-PEI, br-PEI, …. Type 1, Type 2, Type 3. SBA-15, MCM-41, MCF, KIL-2, ….
Metal oxides / Carbonates	Hydrotalcite, CaO, Mixed Metal Oxides, Mg/KO, CaO,….

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CO_2 Capture via Solid Composite Amine Sorbent

Adsorbents for PC CO_2 capture

- Ideal Sorbent:
  - Large CO_2 working capacity.
  - Highly CO_2 selective.
  - Fast sorption kinetics.
  - Low energy (heat of adsorption)
  - Water tolerant.

Comparison of different adsorbents

Type	WC	Select CO_2/H_2O	Kinetics	Energy	Water
Physisorbents					
Act Car	√	~	√	√	~
Zeolite	√	~	√	√	X
MOF	~	~	√	√	~
Chemisorbents					
Amine	√	√	~	~	√
Met Ox	√	√	~	X	√

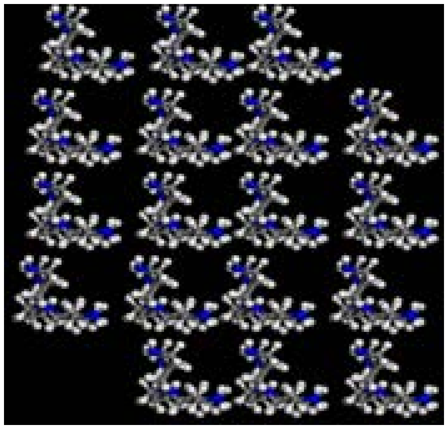
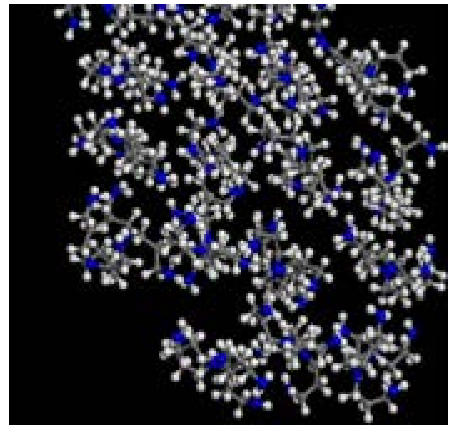
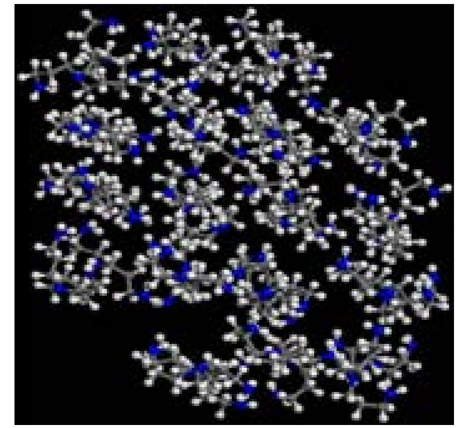
PHYSISORBENTS
Van der Waal's interactions
Electrostatic Interactions
Molecular Size

CHEMISORBENTS
Reactivity
Stoichiometry
Accessibility

Amine Behaviour - Neat vs Supported

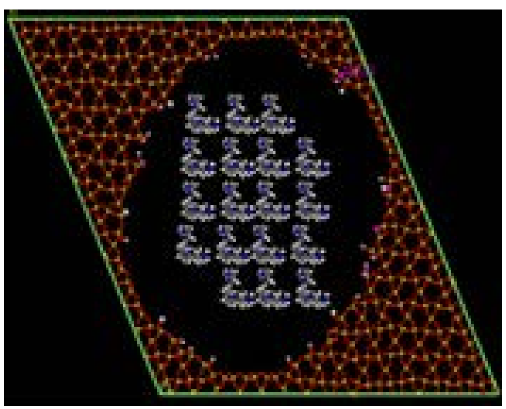
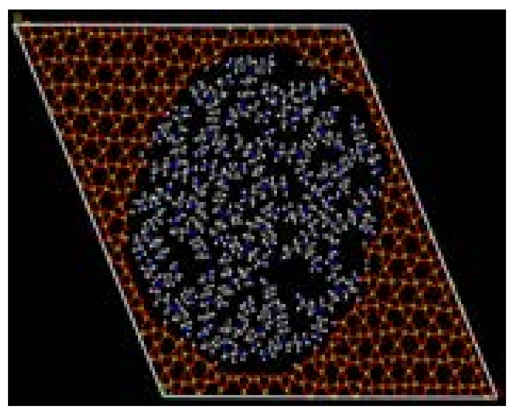
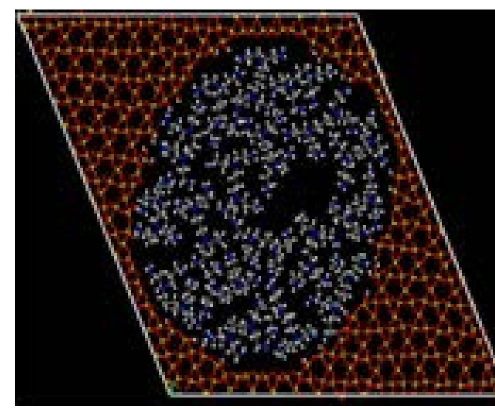
Initial structure | Annealed structure 298K | Annealed structure 378K

Neat

Dendrimer diffusion:	1.19E-07 A^2/ps	1.49E-07 A^2/ps
CO_2 diffusion:	8.89E-06 A^2/ps	2.83E-05 A^2/ps

Impregnated

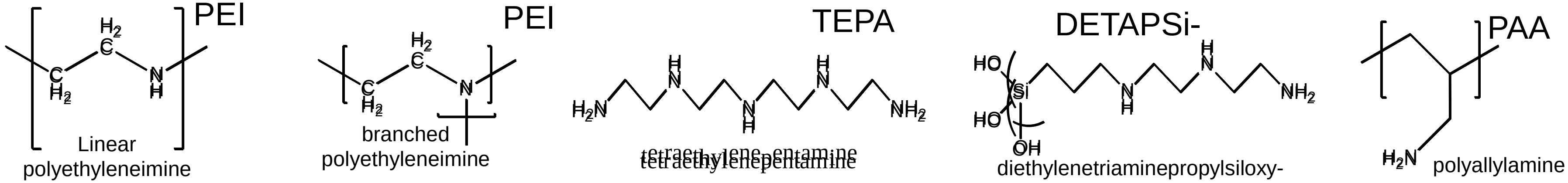




Dendrimer diffusion:	1.53E-05 A^2/ps	4.61E-05 A^2/ps
CO_2 diffusion:	6.49E-03 A^2/ps	1.02E-02 A^2/ps

Fadhel Hearne, Chaffee, MMM 123, 140 (2009)

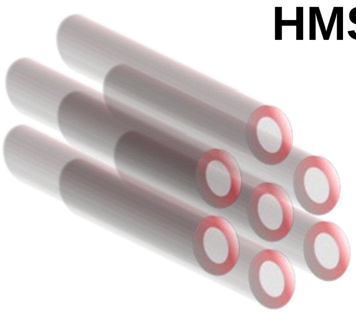
Amine Composites: volume utilisation

- Amines for chemiselective capture, analogous to solvents
- Silica support to 'activate' and contain the active agent and to facilitate vacuum swing adsorption (VSA)



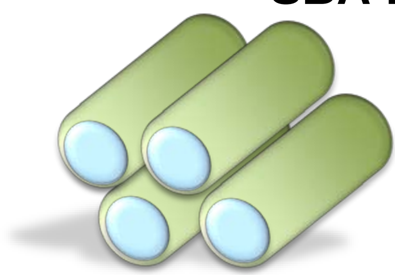
Composites: mesoporous supports incorporating <u>amines</u> Chemisorption

HMS



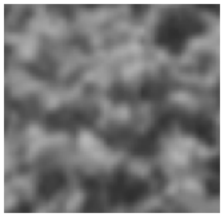
Pore Vol ~ 0.7 mL/g

SBA-15



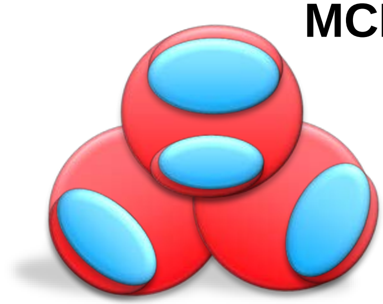
Pore Vol ~ 1.0 mL/g

KIL-2



Pore Vol ~ 1.6 mL/g

MCF



Pore Vol ~ 2.8 mL/g

KIL-2: Wormhole structures with high pore volume

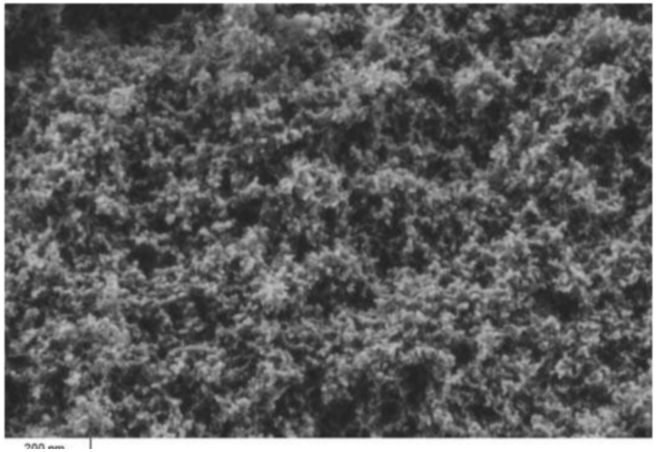


Table 1. Textural properties of KIL-2 materials.

Sample	BET Surface area (m^2/g)	Total pore volume V_{BJH} (cm^3/g)	Average pore size (nm)
KIL-2	702	1.61	9.55
KIL-2-PEI	127	0.35	9.10
KIL-2-TEPA	177	0.46	8.47

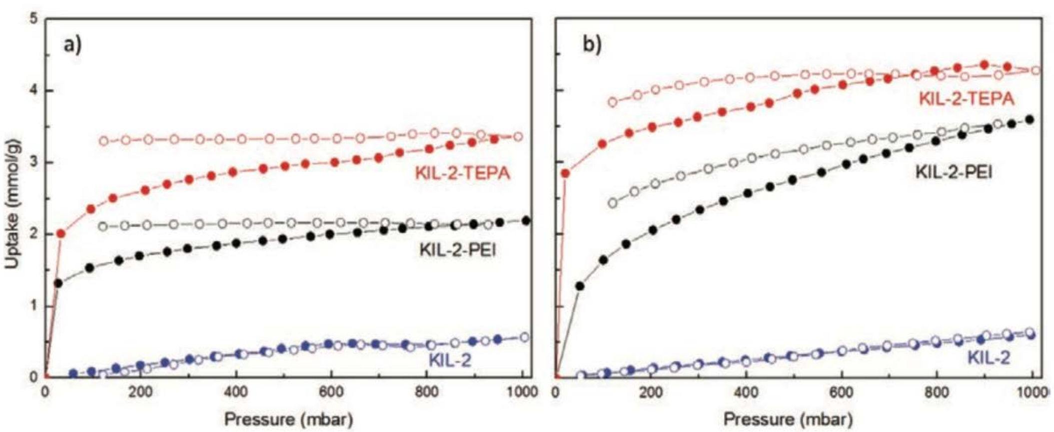


Fig. 2. CO_2 isotherms of KIL-2 materials: a) at 25°C; b) 90°C.

Table 2. CO_2 sorption capacities of amine-impregnated silica materials at 1 bar.

Sample	Temperature (°C)	Amine content (wt.%)	Sorption capacity (mmol CO_2/g ads)	Reference
MSU-J-TEPA-50	25	50	3.73	[32]
	85		1.29	
MSU-J-PEI-50	30	50	2.04	[33]
	100		2.95	
HMS-PEI-50	30	50	2.27	
	100		2.72	
45-PEI/HMS	50	45	2.70	[34]
	90		2.91	
MSU-TEPA	75	50	3.80	[35]
KIL-2-PEI	**25**	**50**	**2.19**	**This work**
	90		**3.60**	
KIL-2-TEPA	**25**	**50**	**3.37**	
	90		**4.35**	

Ojeda et al, Energy Procedia 114 (2017) 2252 – 2258

Amine Composites: volume utilisation

Note sorption dependence on:

- Temperature
- Amine loading as % of pore volume

Water inhibits deactivation by urea formation:

Eq 1: $2RNH_2 + CO_2 \leftrightarrow RNHCOO^- + RNH_3^+$.

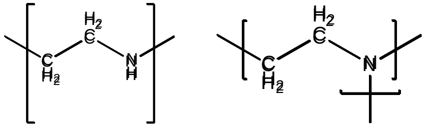
Adsorption (carbamate formation)

Eq 2: $RNCOO^- + RNH_3^+ \leftrightarrow RNCONR + H_2O$

De-activation (urea formation)

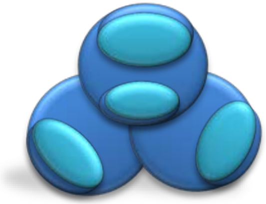
CO_2 Working Capacities:

- ~ 11 wt % CO_2 (TSA, 105 -150 C)
- ~5 wt % CO_2 (VSA, 0.05 -0.15 atm)

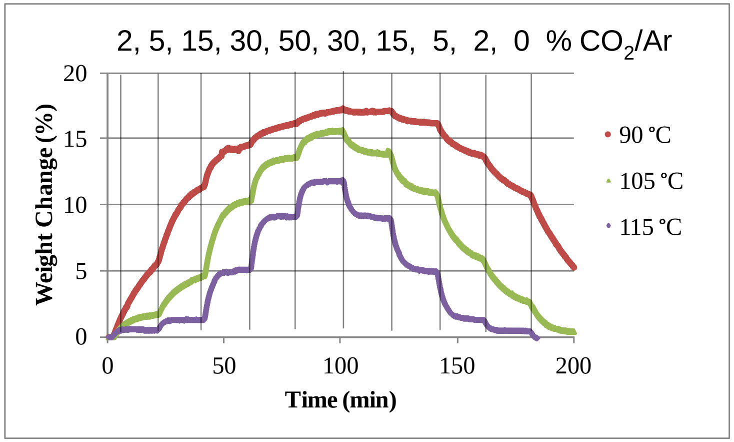


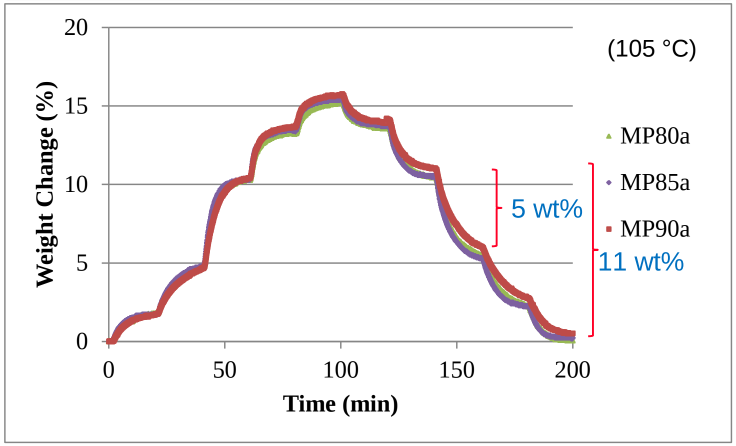
linear branched

Polyethyleneimine (PEI) .



MCF





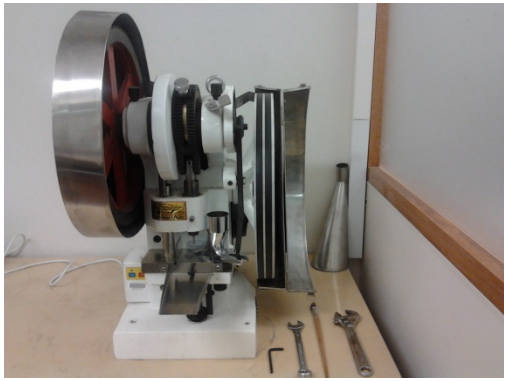
TGA of CO_2 PPSA for MCF-PEI composites.

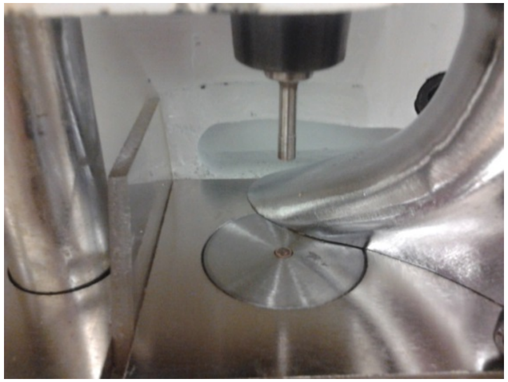
Knowles et al, Micro Meso Mat, **238**, 14 (2017)

Production of MCF-PEI80 pellets via SPTP

- ~80 g MCF.
- ~200 g MCF-PEI (~80 % void vol. fill).
- Shaped as carbonated via SPTP.

~1 g amounts of MCF-PEI80b before (left) and after (right) shaping via SPTP[1].





Automated Single Punch Tablet Press

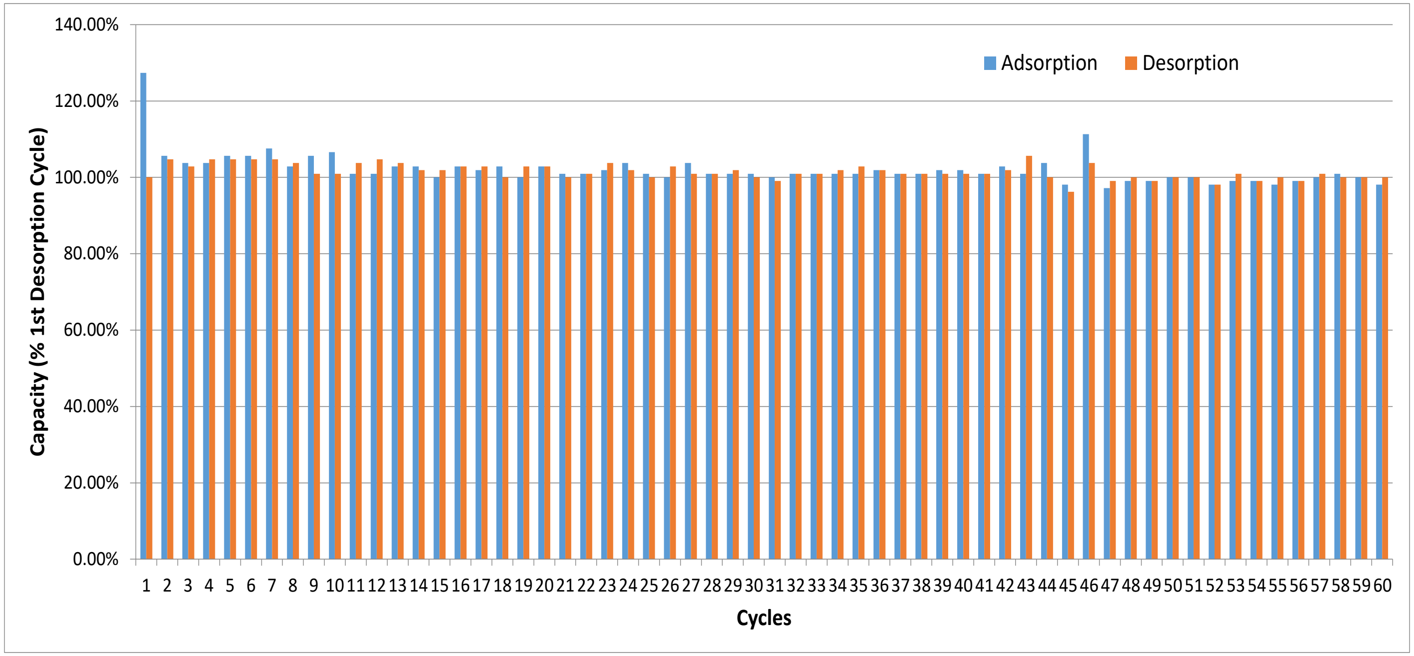
New shaping technology appears scalable for mass automated production

[1]Carbon Capture Journal, "Monash University develops new shaping technology to produce sorbents", 2015, July-Aug edition, pages 12-13,

Amine Composites: volume utilisation

Simulated Flue Gas

These improvements in PEI sorbents provide stability for PCC

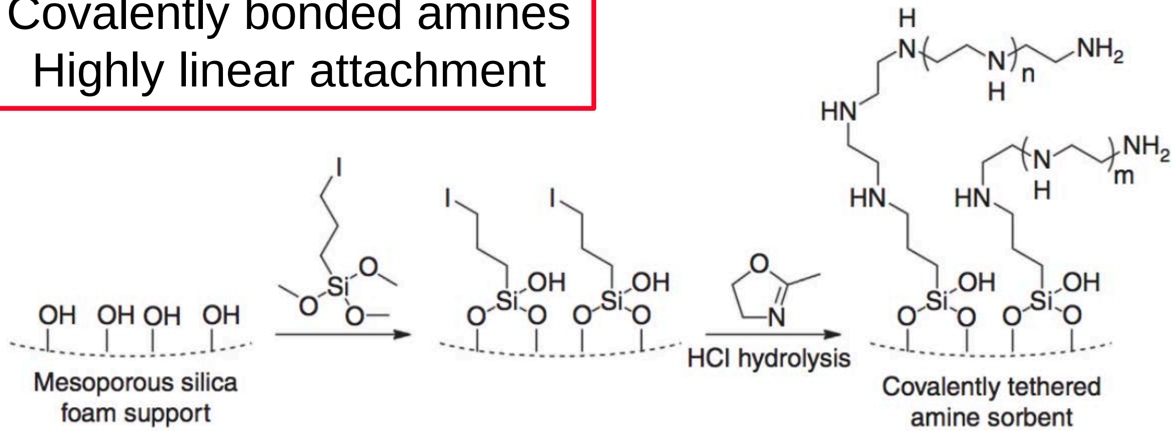


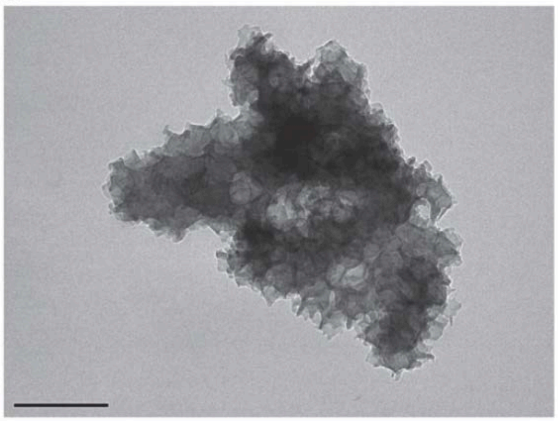
CO_2 working capacity preserved over 60 cycles partial pressure swing adsorption (VSA) at 105 °C

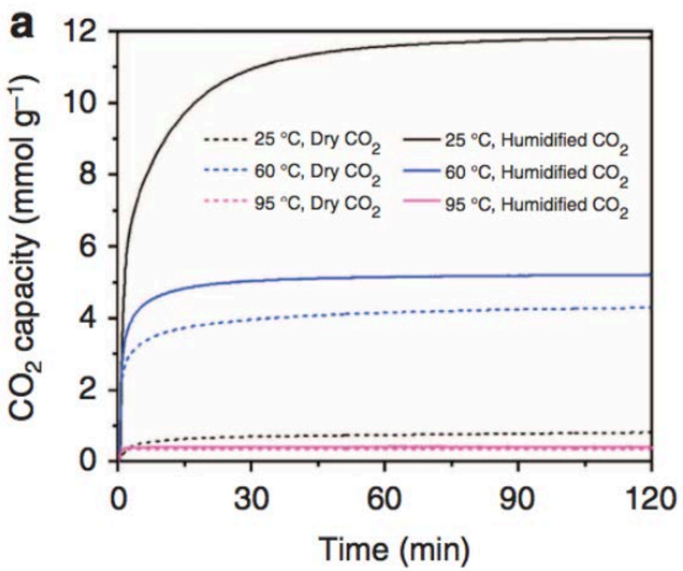
Knowles et al, 2016, unpublished results

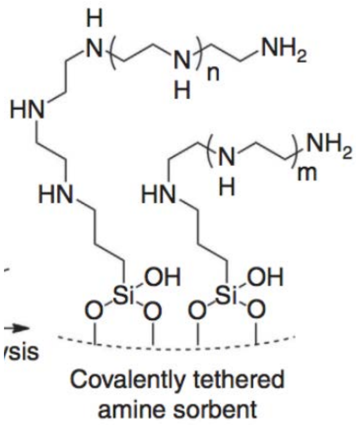
Amine Composites: increasing capacity further

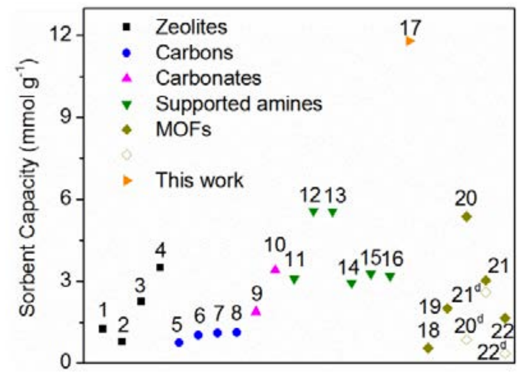
Covalently bonded amines
Highly linear attachment











Qi et al, Nat. Commun. 2014, 5, 5796

Amine Composites: Improving the Stability of PEI adsorbents

The problem - urea formation:

$$R^1R^2NH + CO_2 + R^3R^4NH \Leftrightarrow R^1R^2NCONR^3R^4 + H_2O$$

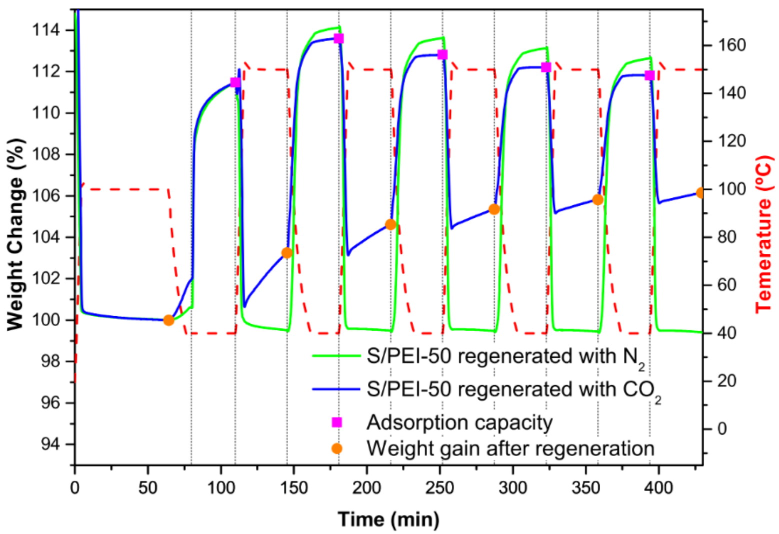
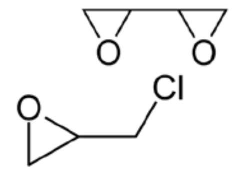
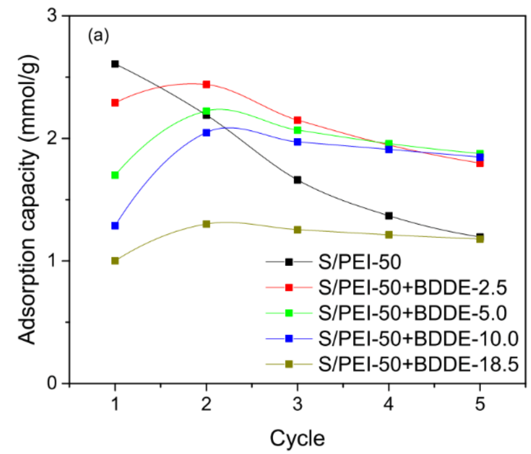


Fig. 1. Weight and temperature profiles for S/PEI-50 in the adsorption-regeneration cyclic tests.

One solution – cross linking with:

butadiene diepoxide
epichlorohydrin





Capacity loss with cycling is reduced

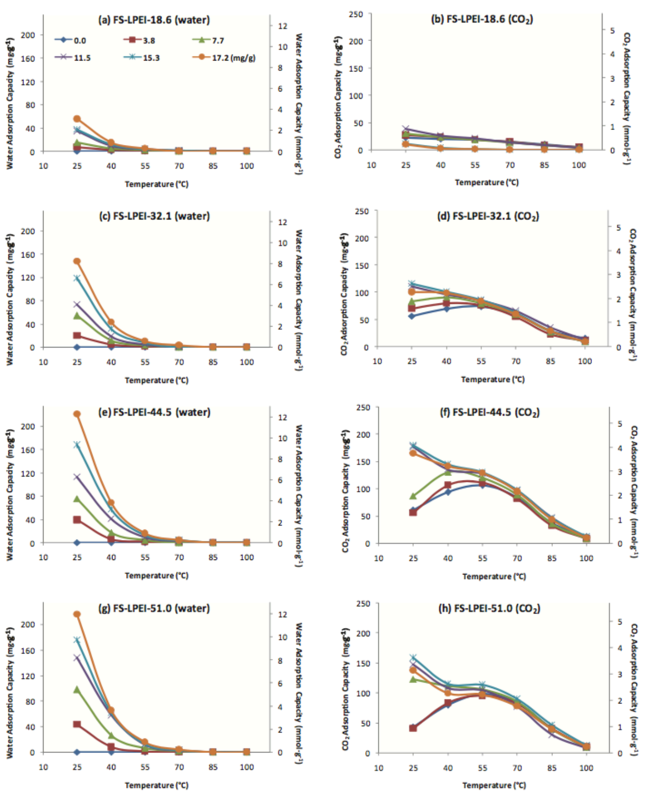
Table 2
Amine ratio of pristine and crosslinked PEIs calculated from ^{13}C NMR analysis.

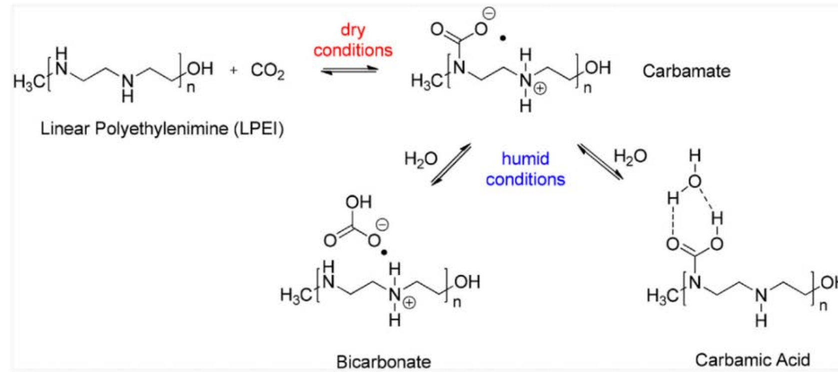
Sample	Amines (%)		
	Primary	Secondary	Tertiary
PEI	36.6	34.3	29.1
PEI+BDDE-2.5	33.5	36.2	30.3
PEI+ECH-2.5	34.1	35.8	30.1

H Jung et al, Chem Eng J 307 (2017) 836–844

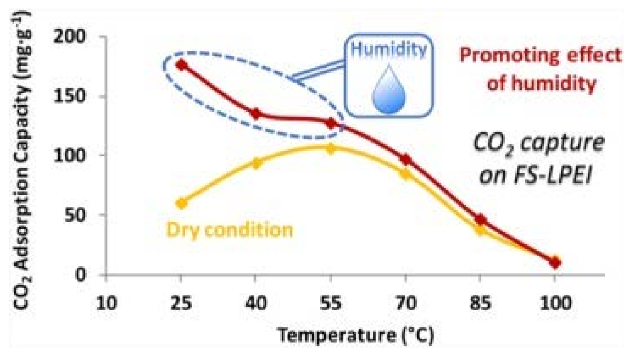
'Exhaustive study' of effect of T and <u>$p(H_2O)$</u>

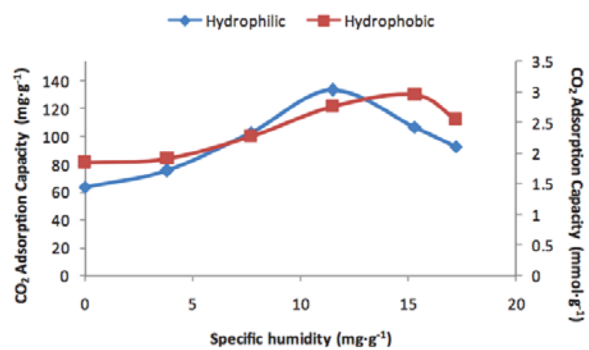
- H_2O adsorption isotherms
- CO_2 adsorption isotherms





Scheme 1. Proposed adsorption mechanisms between CO_2 and linear polyethylenimine (LPEI) under dry and humid conditions.





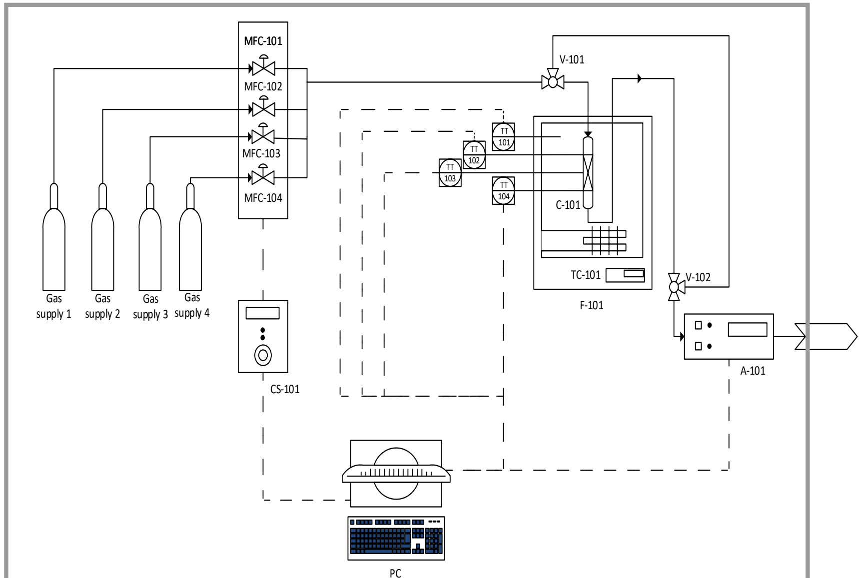
Water adsorbs at low T and promotes CO_2 adsorption at low T

At higher T little water adsorbs and, so, doesn't make energy demands during Desoprtion.

H. Zhang et al, J CO_2 Utilization 19 (2017) 91–99
Prakrash / Olah group

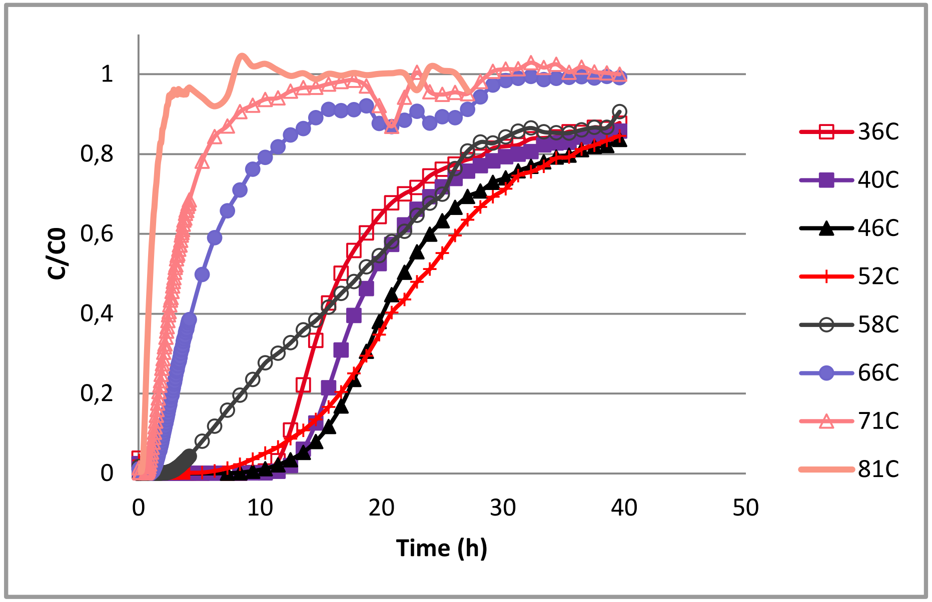
MCF-PEI Pellets: Applying this to Air Adsorption

Breakthrough Apparatus



Simulated Air (400 ppm CO_2 in N_2)
Flow rate: 270 mL/min

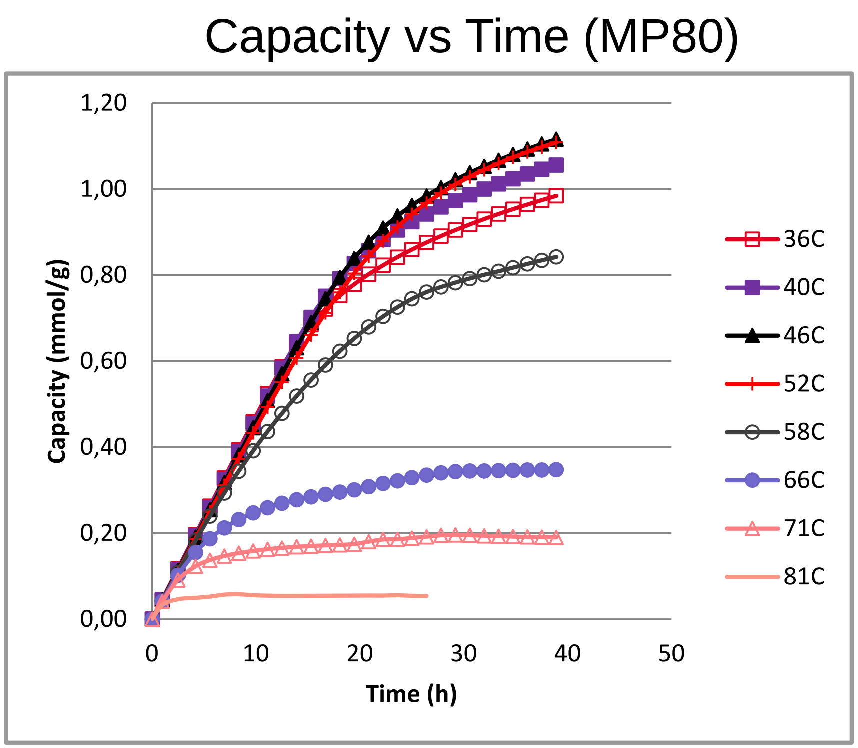
Breakthrough Curves

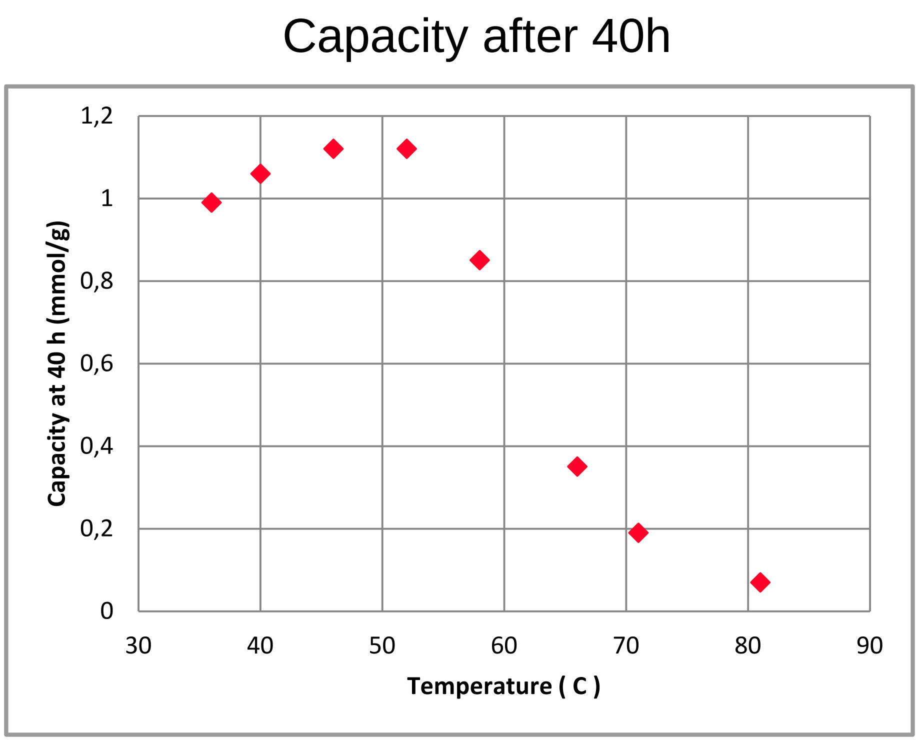


Breakthrough time is very temperature dependent
Saturation is achieved only above 60 C over the time scale studied.

Wijiseri et al, Chemeca, Melbourne (2017)

MCF-PEI Pellets for Air Adsorption





Capacity is temperature dependent
Optimal temperature is ~ 50 C (max CO_2 adsorption rate)
Probably can be improved at lower PEI loadings
CO_2 would be recovered with low grade heat

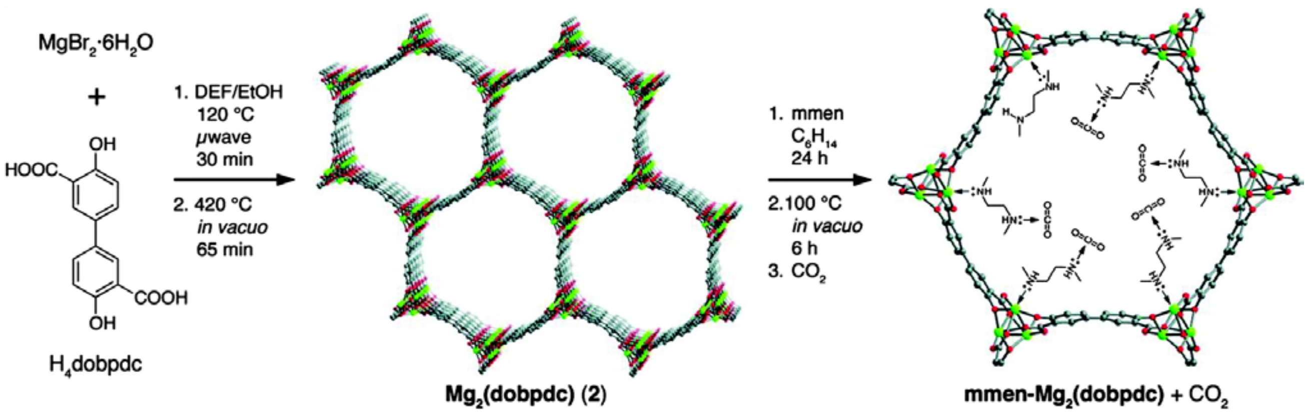
Wijiseri et al, Chemeca, Melbourne (2017)

Materials – multitude of variations

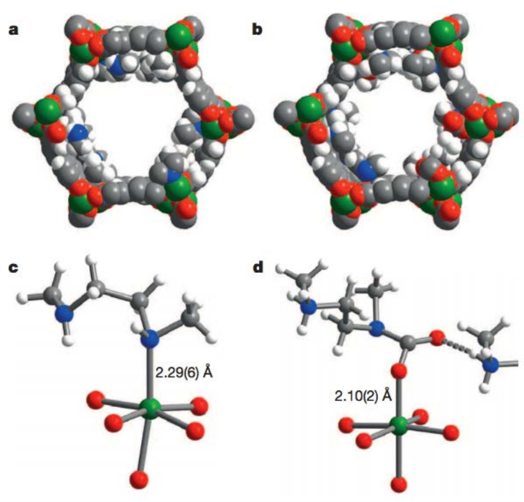
Chmisorbents vs. Physisorbents

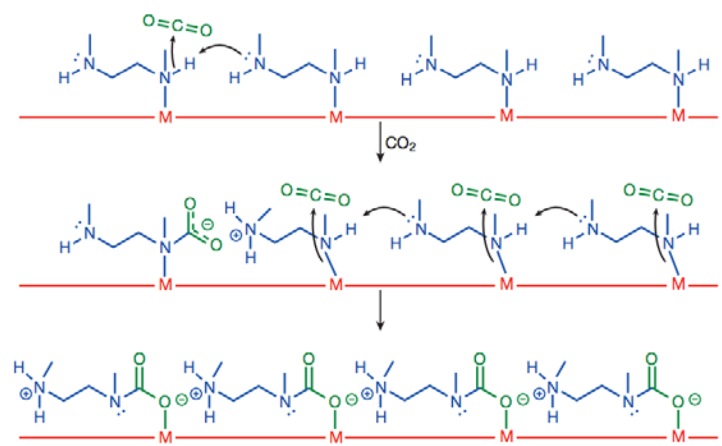
Carbons	Microporous, mesoporous, nanoporous, graphitic, … Templated, MWNT, SWNT, carbon fibres, …. C-molecular sieves, N-doped,…
Zeolites	Type X, Y, A, MOR, CHA, HZMS5, H-form, Na-form, Ca-form, Mg-form,….. Molecular sieves
MOFs	MOFs, ZIFS, COFs,… HKUST, DMOF, UiO-66, UTSA, MIL-101, IRMOF-8,…. Zn-DABCO, Co-DABCO, Mg/DOBDC, ZNBuBPDC, …. mmem-MOFs, IRMOF-8-NO2,….
Amine composites	PEI, TEPA, linear-PEI, br-PEI, …. Type 1, Type 2, Type 3. SBA-15, MCM-41, MCF, KIL-2, ….
Metal oxides / Carbonates	Hydrotalcite, CaO, Mixed Metal Oxides, Mg/KO, CaO,….

MOFS: New prospects with ‘Phase Change Adsorbents’



Reversible
Cooperative
Insertion





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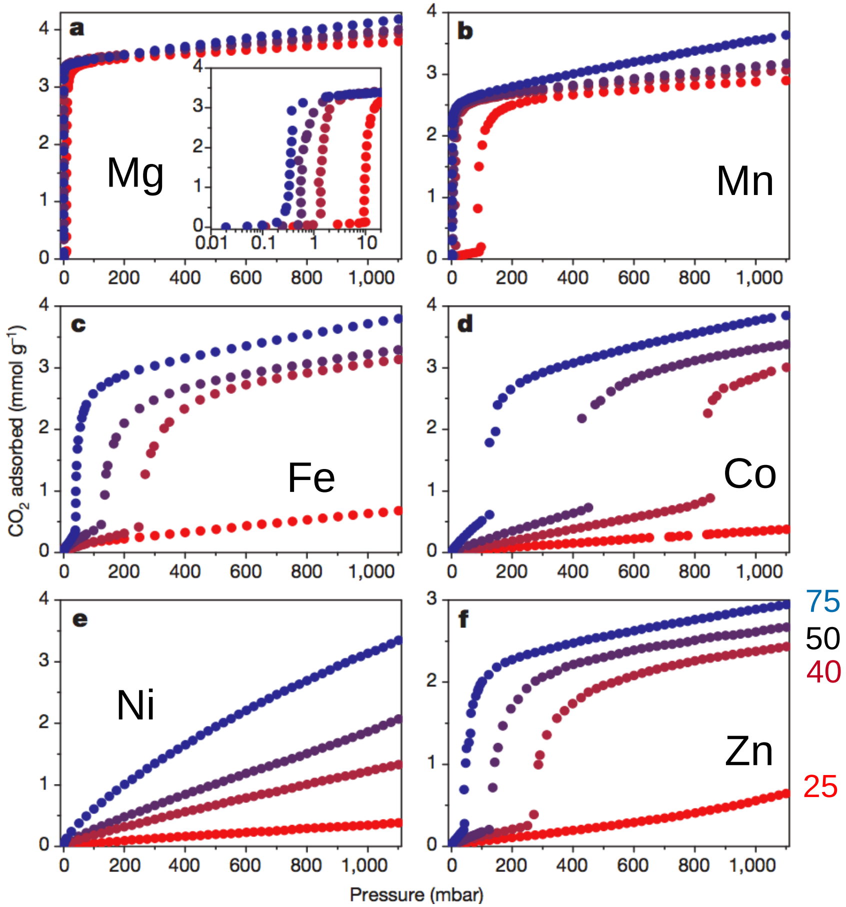
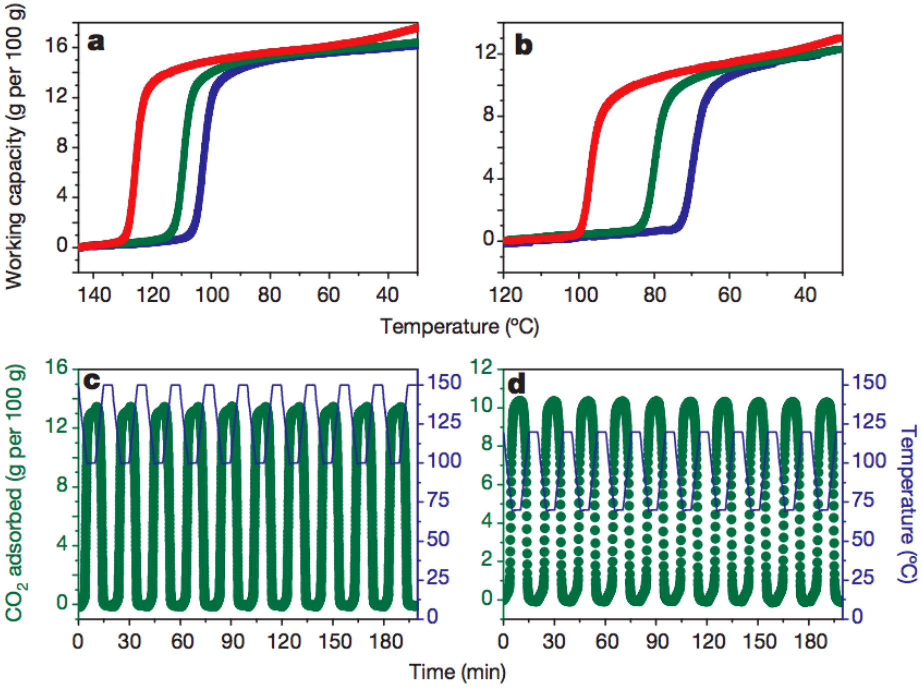
Chem. Soc. Rev., 43, 5952-5981 (2014)
Long et al, Nature 519, 303–308 (2015)

Phase Change Adsorbents

CO_2 Adsorption Isotherms



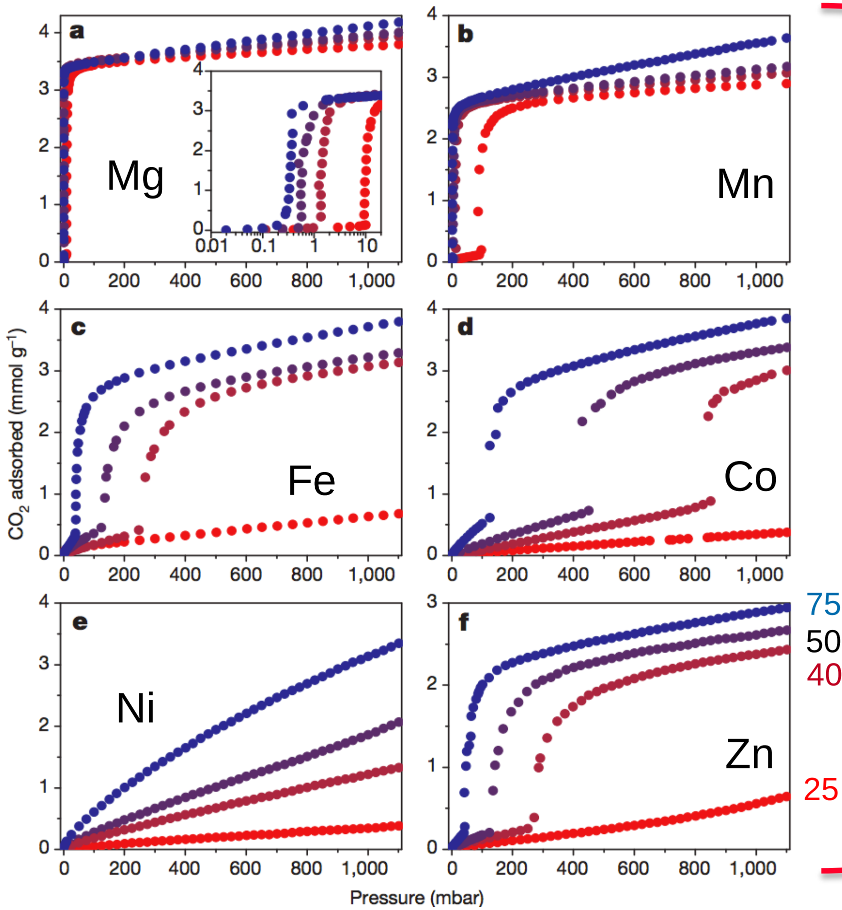
CO_2 Adsorption Isobars



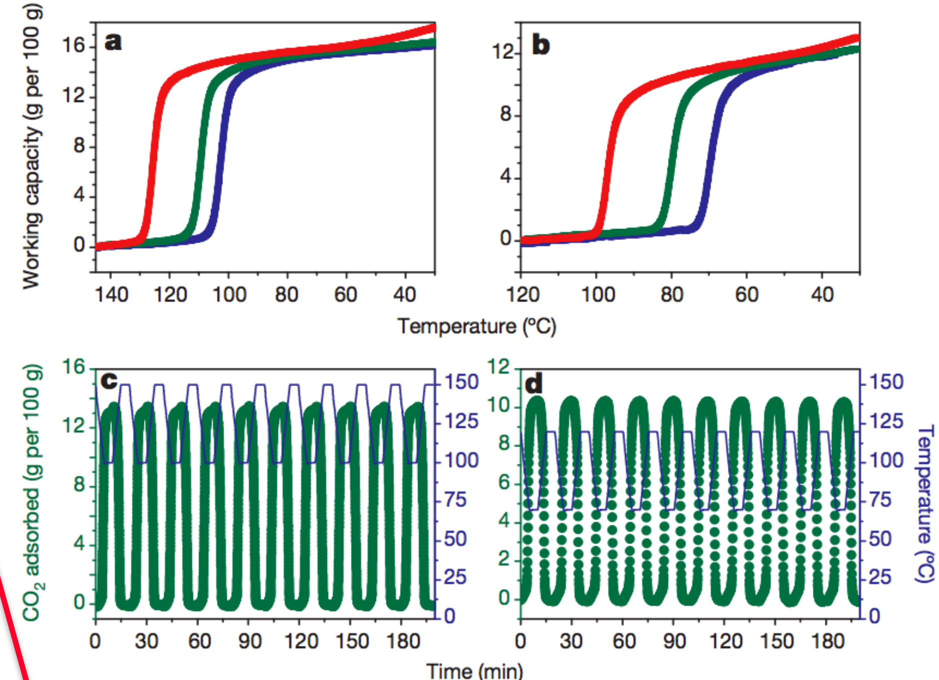
Long et al, Nature 519, 303–308 (2015)

Phase Change Adsorbents

CO_2 Adsorption Isotherms



CO_2 Adsorption Isobars

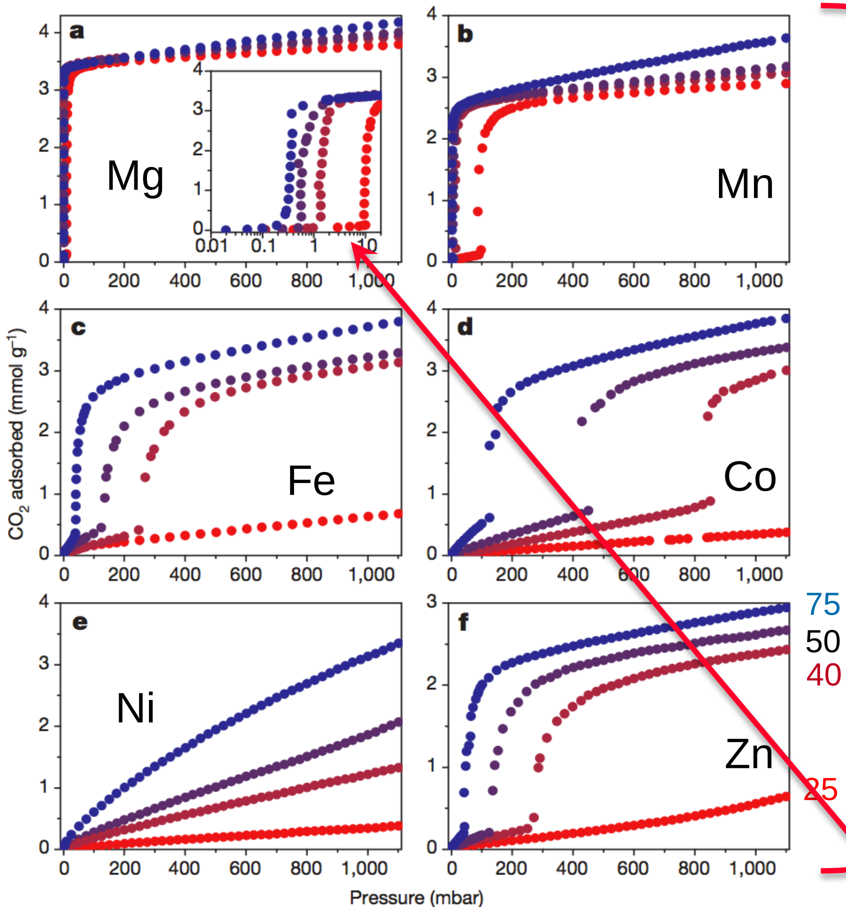


‘Switch’ occurs over a wide range of P and T, depending on metal

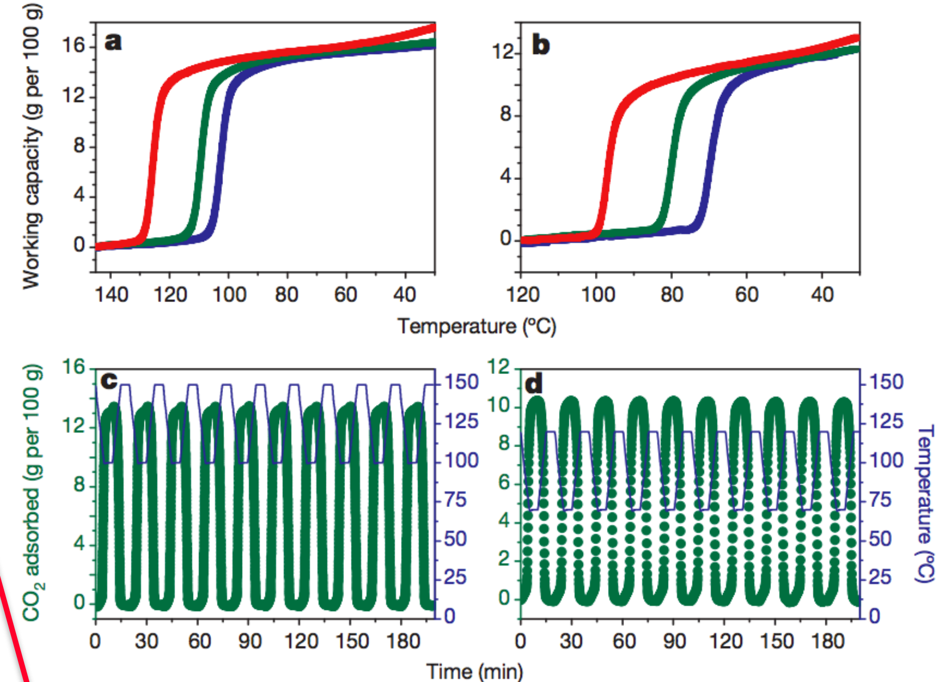
Long et al, Nature 519, 303–308 (2015)

Phase Change Adsorbents

CO_2 Adsorption Isotherms



CO_2 Adsorption Isobars



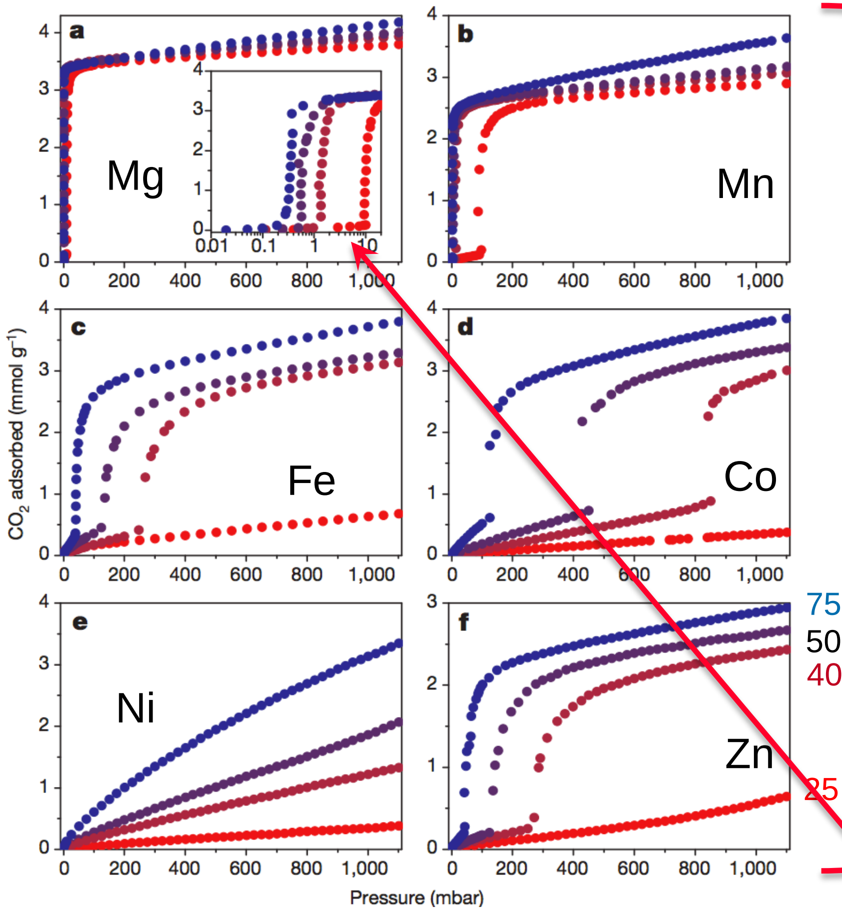
‘Switch’ occurs over a wide range of P and T, depending on metal

Appreciable CO2 adsorption from air

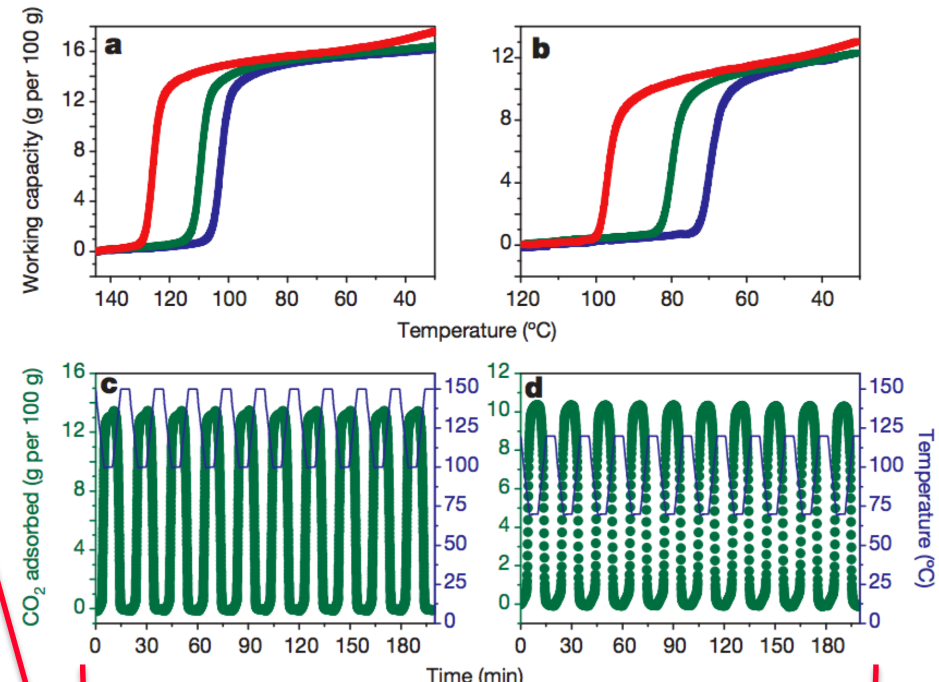
Long et al, Nature 519, 303–308 (2015)

Phase Change Adsorbents

CO_2 Adsorption Isotherms



CO_2 Adsorption Isobars



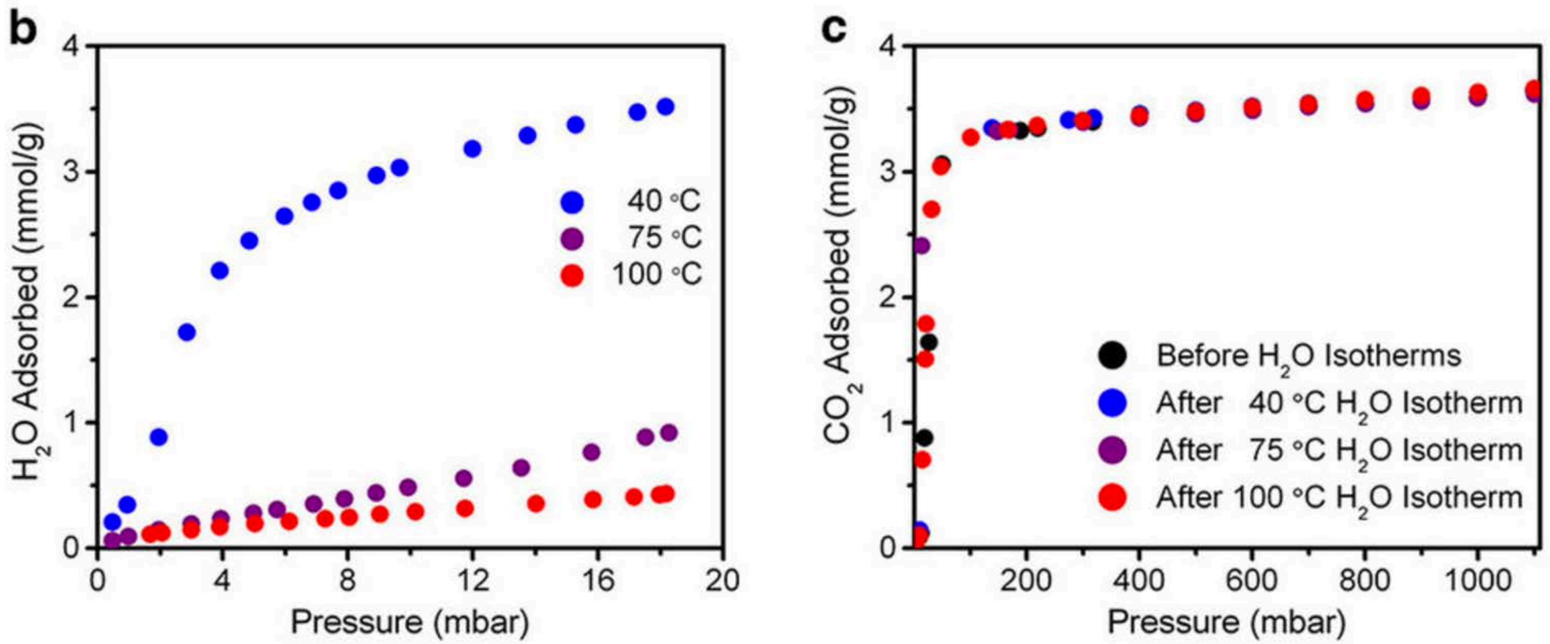
TSA in pure CO_2

'Switch' occurs over a wide range of P and T, depending on metal

Appreciable CO_2 adsorption from air

Long et al, Nature 519, 303–308 (2015)

Phase Change Adsorbents



These MOFs tolerate moisture!
Exhibit some analgous behaviour to amine composites

Can they be fabricated into industrial robust forms, eg pellets?

Long et al, Nature 519, 303–308 (2015)

Materials – multitude of variations

Chmisorbents vs. Physisorbents

Carbons	Microporous, mesoporous, nanoporous, graphitic, … Templated, MWNT, SWNT, carbon fibres, …. C-molecular sieves, N-doped, Metal hydroxide-doped…
Zeolites	Type X, Y, A, MOR, CHA, HZMS5, H-form, Na-form, Ca-form, Mg-form,….. Molecular sieves
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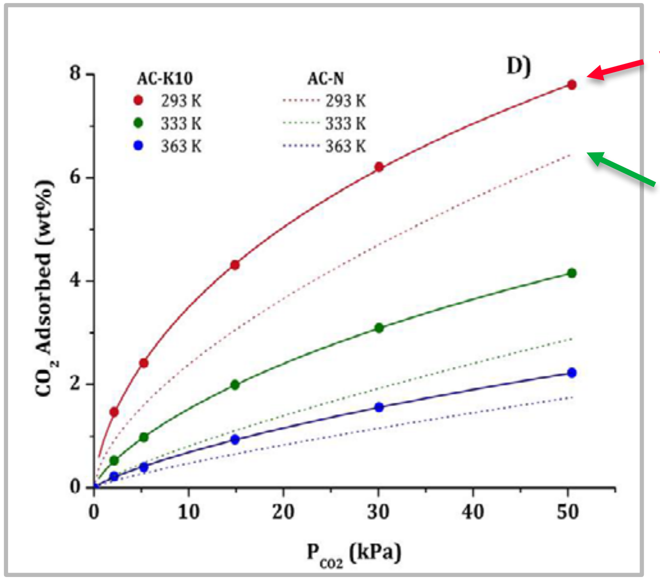
Metal oxides / Carbonates	Hydrotalcite, CaO, Mixed Metal Oxides, Mg/KO, CaO,….

Active Carbon for CO_2 Capture: from brown coal

Victorian brown coal (VBC):

- low S/P/N and low ash make this an excellent precursor for active carbons
- a very cheap resource
- enormous surface areas can be achieved (>1000m^2/g)
- this results in excellent gas adsorption properties.

CO_2 adsorption isotherms

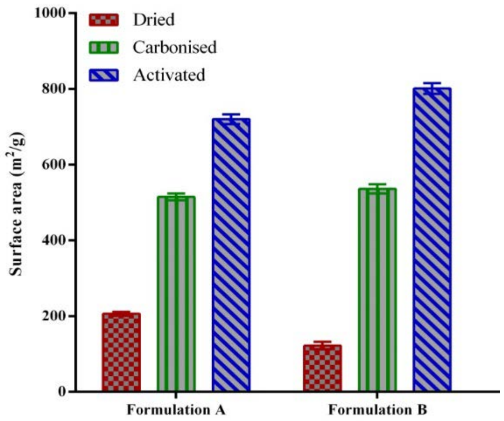


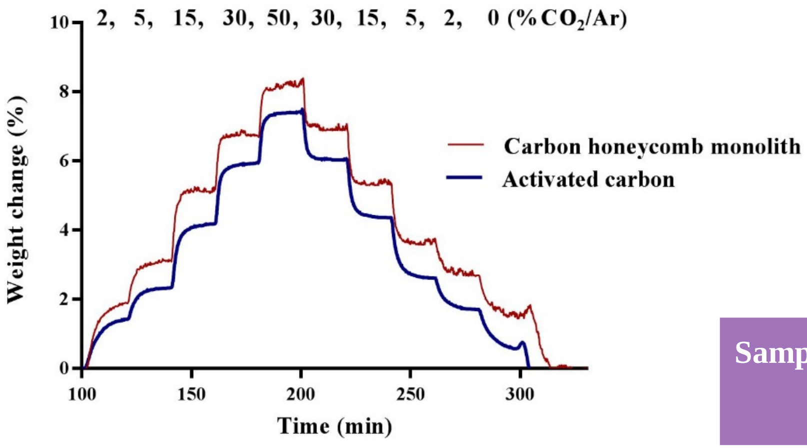
L Ciddor, PhD Thesis, Monash University, 2016

Active Carbon **Monoliths** for CO_2 Capture

A method has been developed to prepare active carbon monoliths from Victorian brown coal

- good surface area
- good electrical conductivity
- good CO_2 adsorption and selectivity

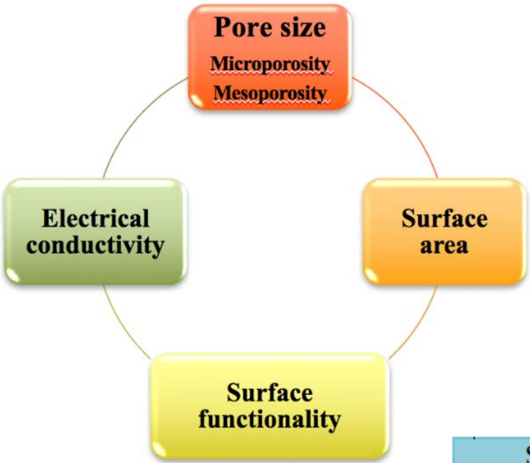




Samples	Cell density (cells/in²)	Wall thickness (mm)	Electrical Conductivity ($\Omega^{-1}cm^{-1}$)		Compressive hardness (MPa)
			Carbonised	Activated	
Formula A	470	0.2	1.88	1.95	20.03
Formula B	470	0.2	0.34	0.49	24.2

Australian Patent Application AU2016901978

Honeycomb Carbon Monoliths from VBC



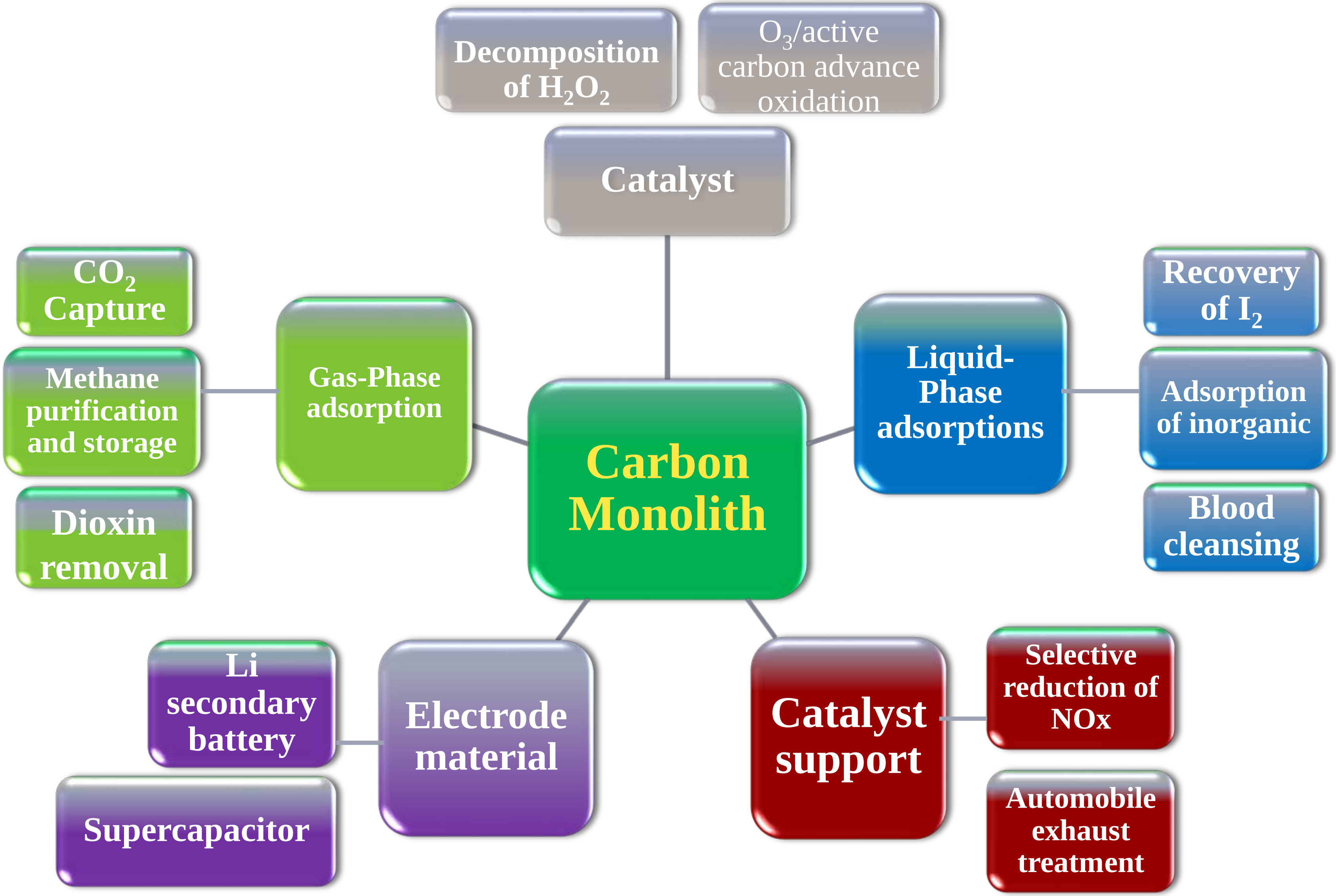
Regenerable
Electrical conductive
High surface area
Easy to make
Light weight and high-strength

Samples	Cell density (cells/in^2)	CO_2 Surface area (m^2/g)			Conductivity ($\Omega^{-1}cm^{-1}$)		Compressive strength (MPa)
		Dried	Carbonized	Activated	Carbonized	Activated	
1 kg VBC (formulation A)	470	206	501	721	6.8	7.1	20.03
1kg VBC (formulation B)	470	123	537	1050	0.8	1.8	19.2
1kg VBC (formulation D)	470	118	478	726	1.2	1.5	19.5
Polymer coated cordierite HM [1]	232			680		0.035	
Integral HM from powdered coal [2]	50						17

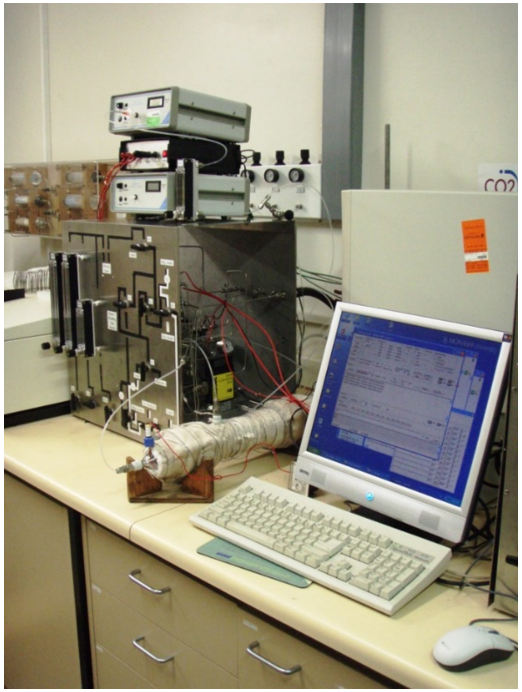
MONASH University

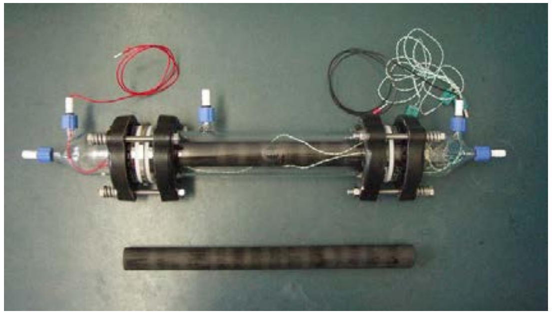
1. Vergunst et al, *Preparation of carbon-coated monolithic supports.* Carbon, 2002. **40**, 1891-1902
2. Liu et al., *Preparation of activated carbon honeycomb monolith directly from coal.* Carbon, 2006. **44**, 1598

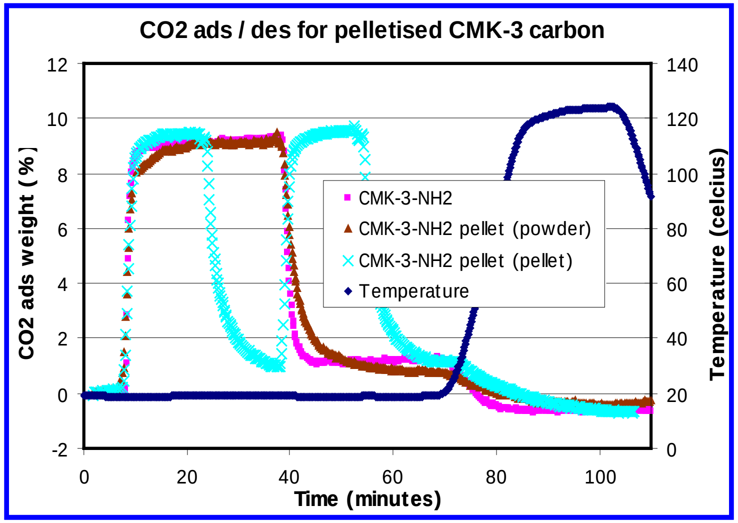
Applications

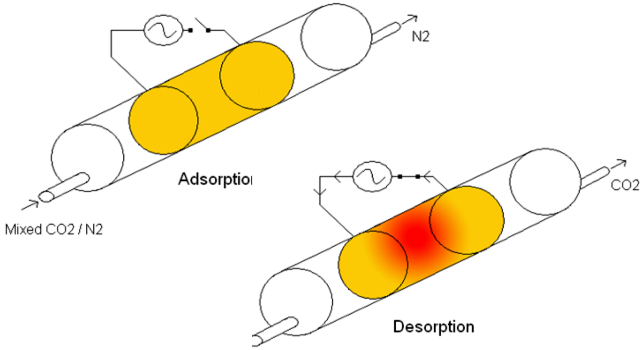


Active Carbon Monoliths for CO_2 Capture



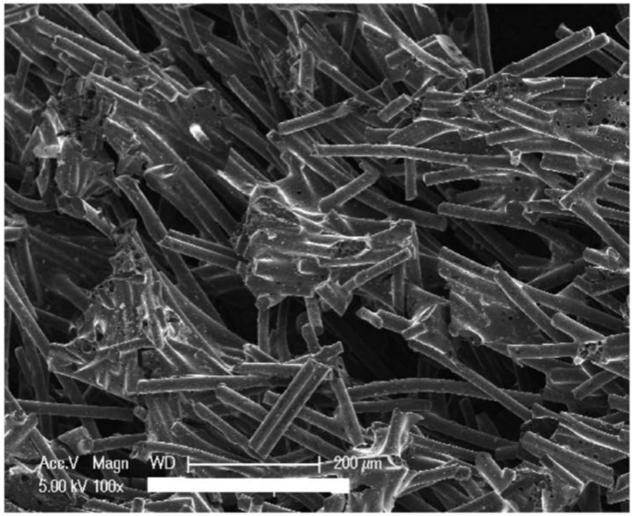


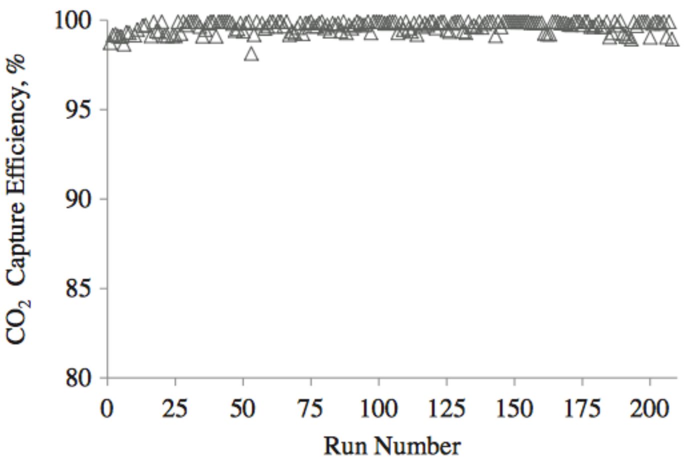




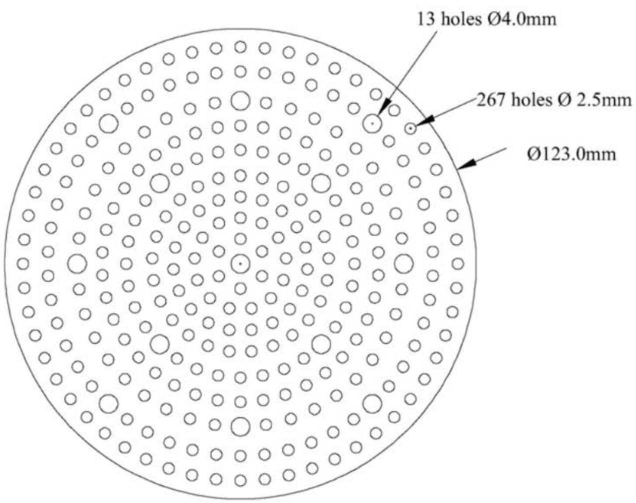
- We have previously demonstrated that monolithic carbons can capture CO_2 and then be regenerated by Electrical Swing Adsorption (ESA)
- This previous work involved expensive precursor materials and/or processing methods
- VBC derived adsorbents are now prospective for CO_2 capture and many other applications.
- Heat is not wasted in regeneration

Carbon Fibre Monoliths





(a)

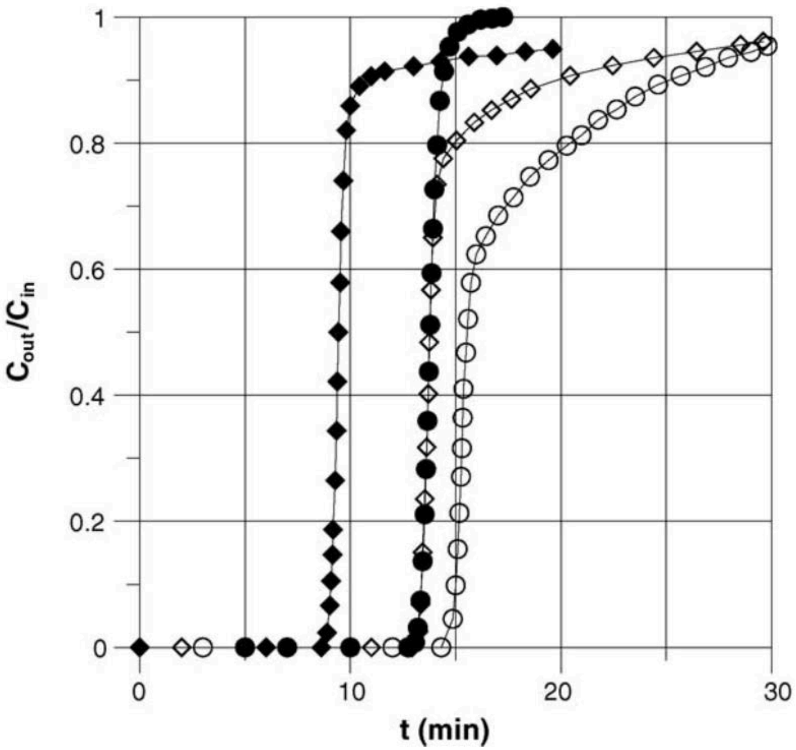


Made from:
petroleum pitch carbon fibre and phenolic resin

Preparation steps:
moulding,
drying and curing,
carbonisation and activation.

Int J GHG Control 13 (2013) 191–200
Int J GHG Control 42 (2015) 415–423

Carbon monoliths: beneficial heat conduction properties



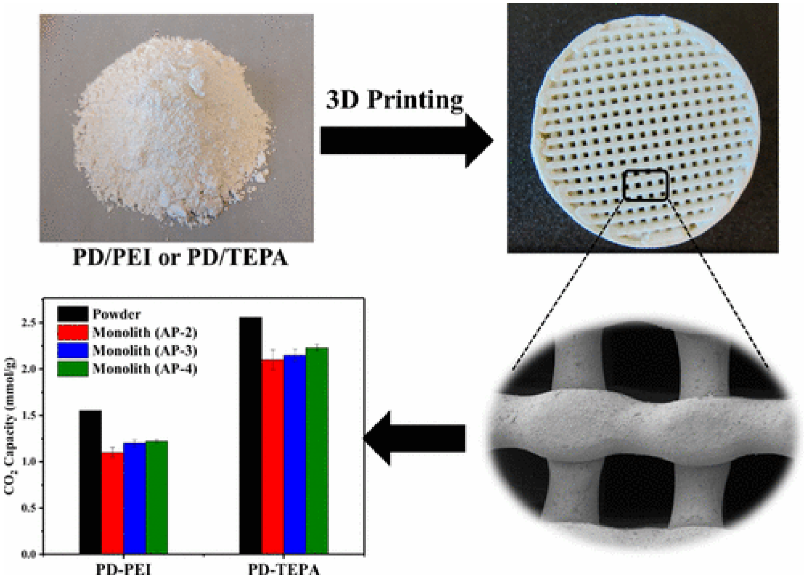
GP: Granular packing
(Pica activated carbon)
SCM: Straight open channel monolith
(Air blown pitch/KOH/expanded graphite)

SCM conducts heat throughout better
Gives more uniform T distribution

Pure CO_2 breakthrough curves for both GP and SCM packings. Open symbols: GP, black symbols: SCM, with external heat transfer: (○), near- adiabatic: (♦).

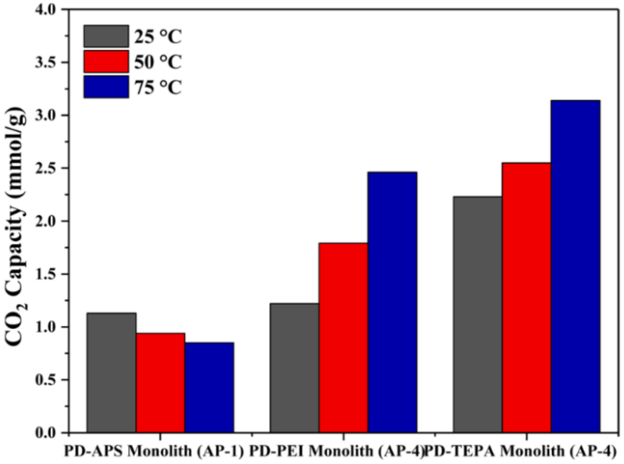
Menard et al, Chem Eng Proc 44 (2005) 1029

PEI Monoliths: 3D Printing



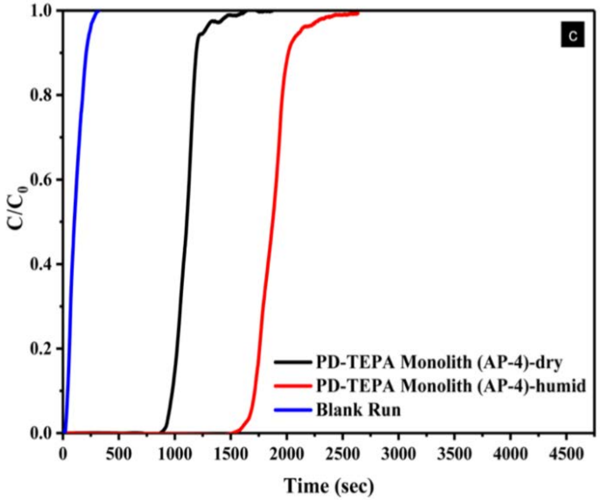
In 10% CO_2/N_2 at 25C determined by TGA

Effects of Temperature



In 10% CO_2/N_2 at variable T, determined by TGA

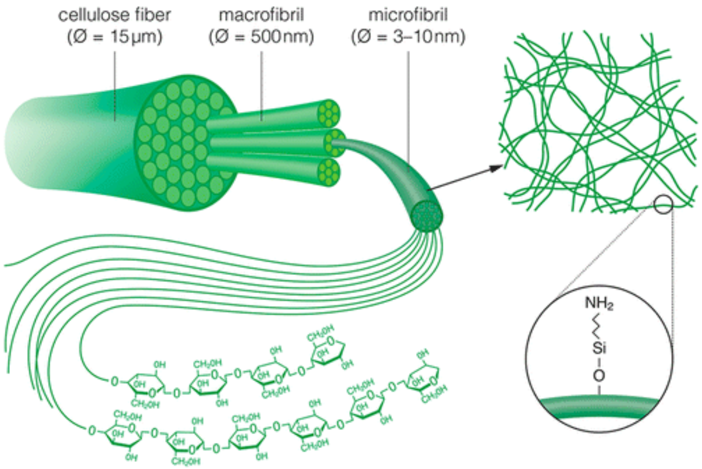
Effects of Moisture



Breakthrough curves at 25C in 10% CO_2/N_2, 30 ml/min

ACS Appl. Mater. Interfaces 2017, 9, 7489
Thakkar et al, Rezaei group

Low Density Structures: Nanofibrillated cellulose (NCF) – aminated



Applied to <u>AIR CAPTURE</u>
TVS process
<u>Adsorption</u>: 30C, 60%RH, 5 l/min, 600 min
<u>Desorption</u>: 90C, 60 min, with moisture (as above), 1 l/min N2, moisture from adsorption,

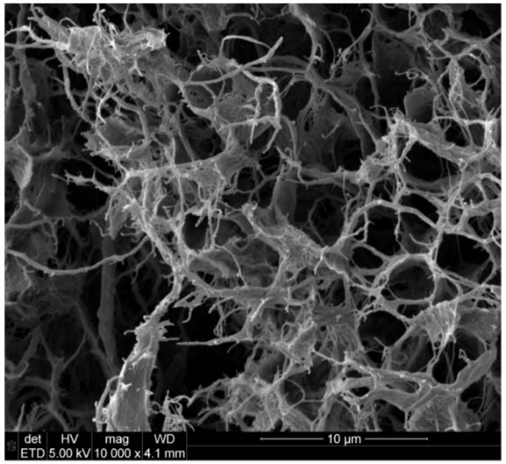
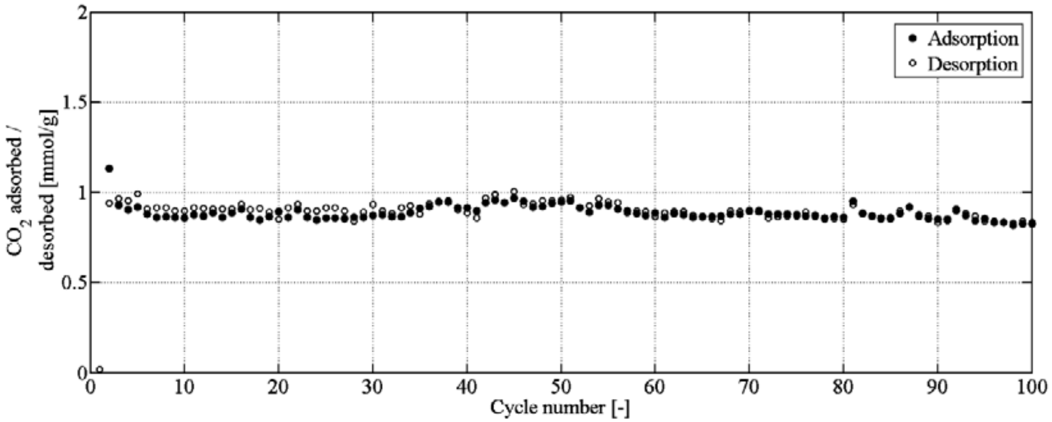
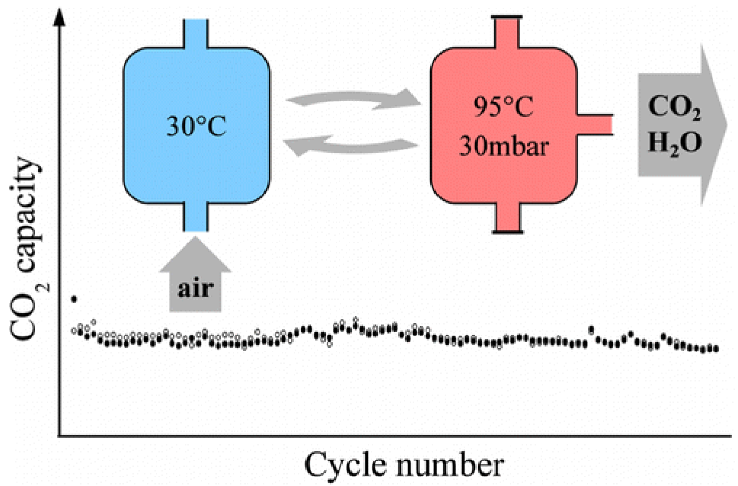


Figure 4. SEM of pristine AEAPDMS-NFC.





Gebald et al, Env Sci & Tech, 2014, **47**, 10063

Phase Change MOFs on Monoliths

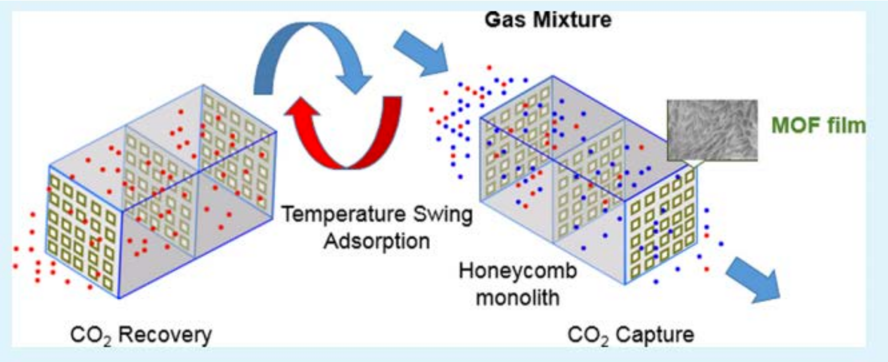
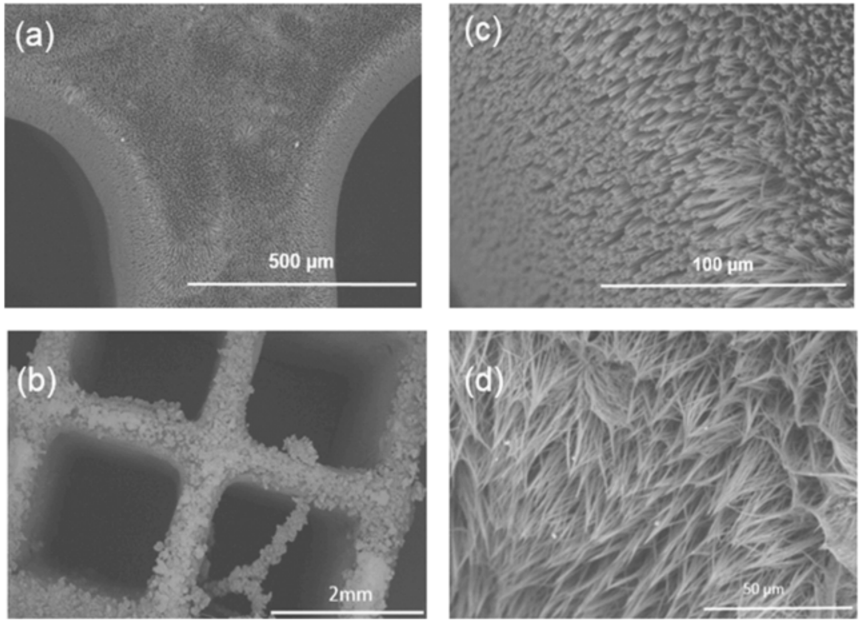
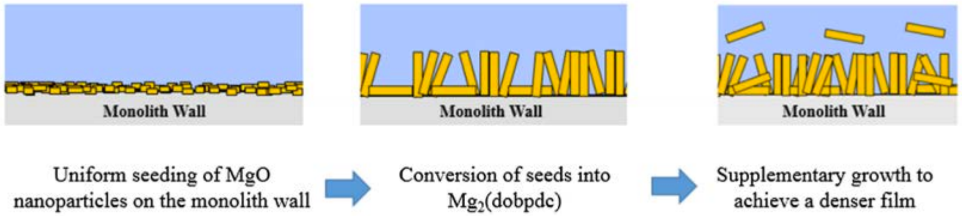


Table 1. CO_2 Adsorption and the BET Surface Area of mmen-Mg_2(dobpdc) and mmen-Mn_2(dobpdc) before and after Exposure to Water

	mmen-Mg_2(dobpdc)		mmen-Mn_2(dobpdc)	
	before H_2O exposure	after H_2O exposure	before H_2O exposure	after H_2O exposure
CO_2 adsorption at 10% CO_2 in helium (mmol/g)	3.33	3.27	3	1.8
BET surface area (m^2/g)	894	645	794	134





Durante et al, ACS Appl Mat Interf, 9, 17042 (2017)
Jones Group

Building Focus on Air Capture

CLIMEWORKS

- Solid Supported Amine
- Based on the work of Gebald and Wurzbacher ETH Zurich

Carbon Engineering

- Aq. Metal Hydroxide
- Based on the work of Keith

Global Thermostat

- Solid Supported Amine
- Based on the work of Jones, Georgia Inst Tech

INFINITREE

- Anionic Exchange Resin
- Based on the work of Lackner, Ariz State Uni

SOLETAIR

- Solid Supported Amine
- Based on work at VTT
- Combined with H_2 from electrolysis to produce FT hydrocarbons

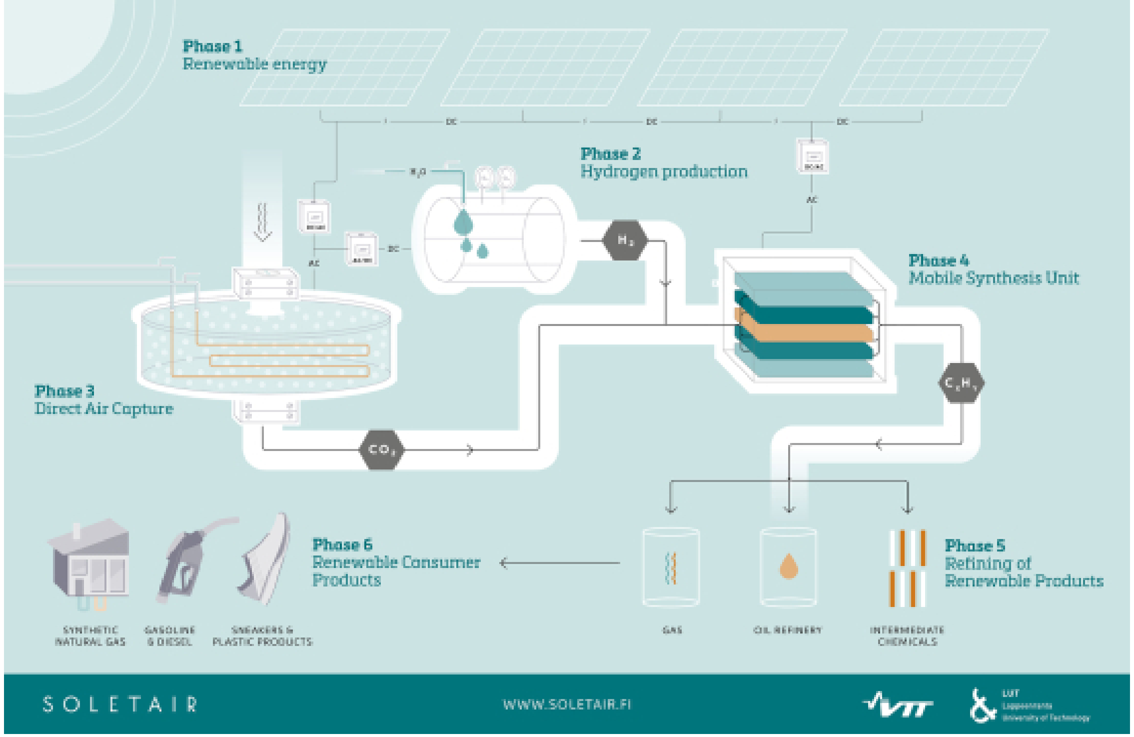
skytree

Building Focus on Air Capture

- Based on the work done at VTT Technical Research Centre of Finland and Lappeenranta University of Technology (LUT)
- Sorbent – amine functionalised polystyrene adsorbent

- Regeneration –
  Heating to 80 °C under vacuum
- Modular unit capturing ~1.5 t-CO_2/yr/module

SOLETAIR



Building Focus on Air Capture

- Spin-off of the work done by Christopher Jones' group at Georgia Tech
- Sorbent - Amine bonded to a ceramic honeycomb monolith support
- Regeneration – Stripping with low temperature steam (85-100 °C)
- CO_2 purity - 98% v/v
- Modular capture units capable of capturing 50,000 t-CO_2/yr/module

http://globalthermostat.com/a-unique-capture-process/

Building Focus on Air Capture

CLIMEWORKS

- Spin-off of the work done by Christoph Gebald and Jan Wurzbacher at ETH Zurich
- Sorbent- Solid supported amine
- Regeneration - heating the sorbent to 100 °C at lowered pressure
- CO_2 purity – 99% v/v
- Collaboration with Audi and Sunfire →Converting the captured CO_2 to “e-diesel”

http://www.climeworks.com/our-technology/

Summary

- MCF-PEI composite powders were prepared at various PEI loadings and shaped into dry robust pellets via a carbonation process.
- These chemisorbent materials have been demonstrated (lab scale) for multiple PCC cycles (105 C) and now need to be trialled at larger scale.
- MCF-PEI materials also work for air separation at lower T – we are investigating process parameters/configurations to optimise this.
- Active carbons prepared from brown coal are also very good adsorbents (physisorbents).
- Brown coal has recently been extruded then carbonised/activated to form multichannelled monoliths that are electrically condutive.
- These can be used directly or functionalised then used in an ESA process to help minimise energy demands for CO_2 capture and recovery

Summary

- What one sees to be important emerging trends really depend on the precursor available, the product(s) forseen, the adsorbent applied and the process selected. It is not easy to glean the best way forward.
- Work on materials continues to strive for better capacities, higher selectivities, reduced energy demands, improved tolerance to impurities (including water), faster cycling, etc. This will support are markets / processes
- The chemoselectivity of amines (in varied forms) is attractive, as is the generalyl robust character and relatively lower cost of active carbons.
- Monoliths are attracting considerable interest due to new methods of fabrication and their inherent low pressure drop.
- Air capture is assuming prominence – it can be done anywhere and, perhaps, combined with renewable H_2 for fuel production.

Acknowledgements

Colleagues:

Dr Greg Knowles, Dr Zhijian Liang for production of the MCF-PEI powder products.
Dr Merhdad Parsa and Dr Emma Qi for production and procesing of VBC carbon monoliths.
Romesh Wijesiri, Prof Andrew Hoadley Dr Hasina Yeasmin, for air capture studies
Dr Seamus Delaney for initial ESA developments
Dr Lachlan Ciddor for VBC derived active carbon powders
Jack Sher, Corinna Henninger, Rahmam Rahad and Zoe Veldmann for laboratory assistance
Prof Paul Webley, Dr Penny Xiao, Uni Melbourne, collaboration on processing routes

Thank You !

MONASH University