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CCS IN ACTION - CRANFIELD BIANNUAL
21-22 April 2015

Novel membranes for carbon capture

Peter M. Budd

Professor of Polymer Chemistry
School of Chemistry
University of Manchester

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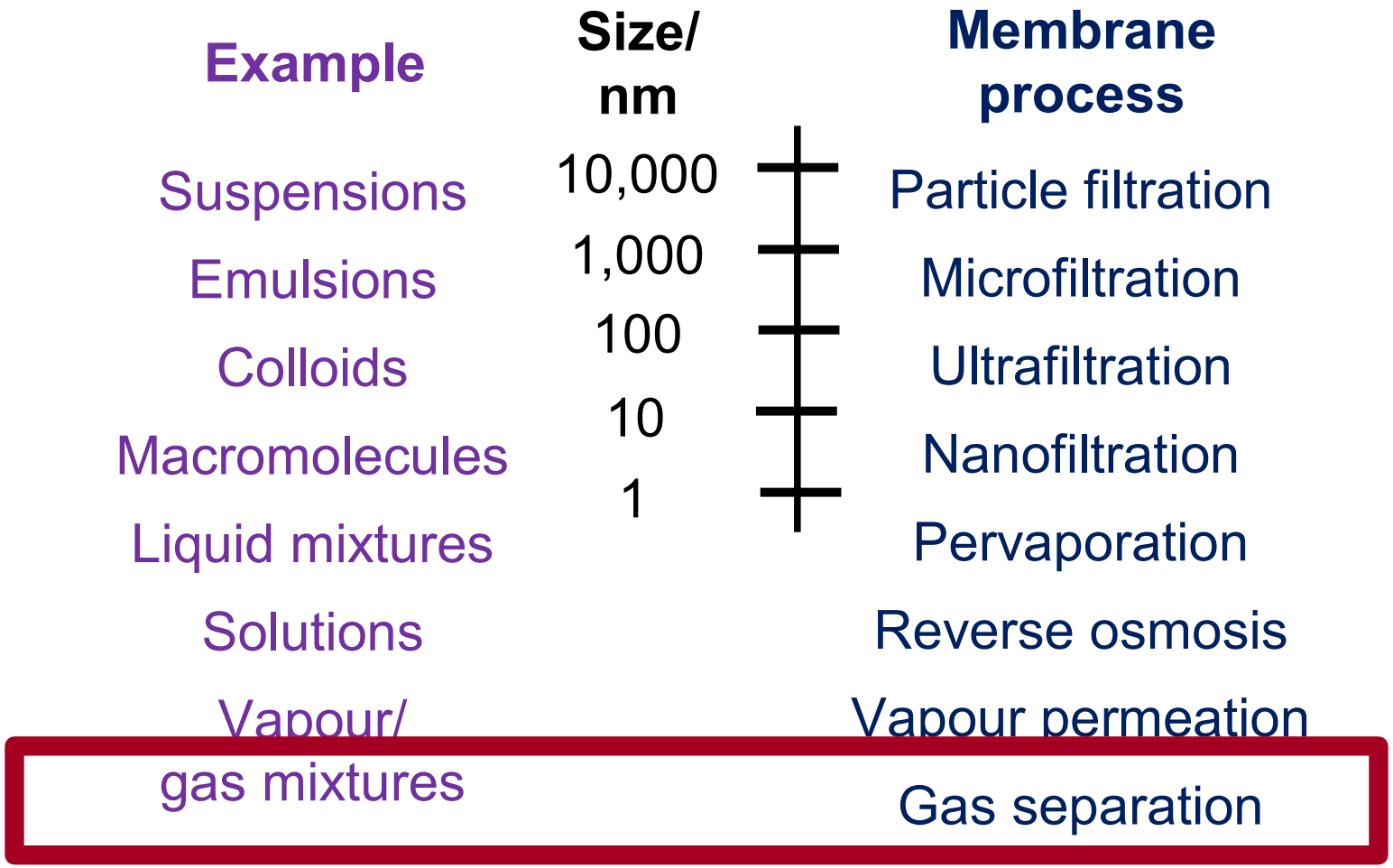
Membrane processes

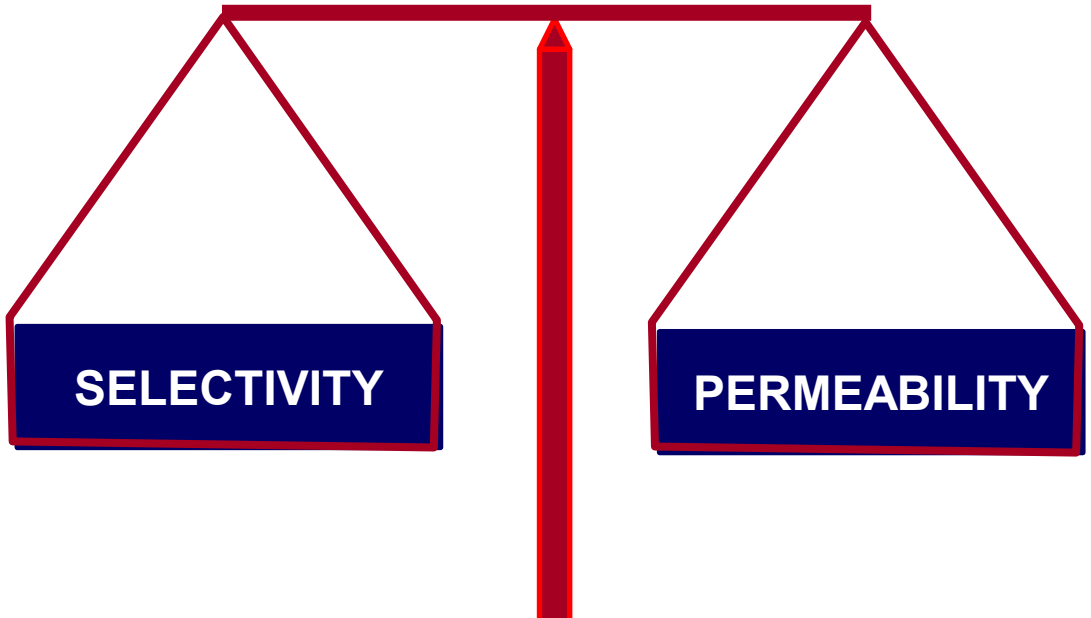


Membrane materials

Requirements

Selectivity

Productivity (permeability, flux)



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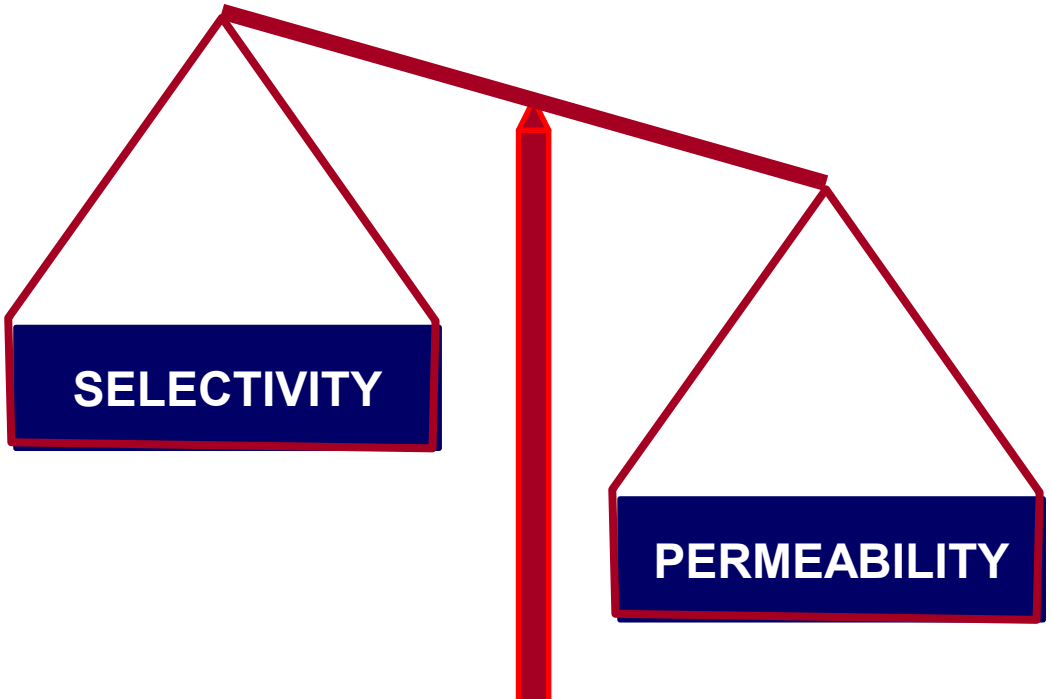

Membrane materials

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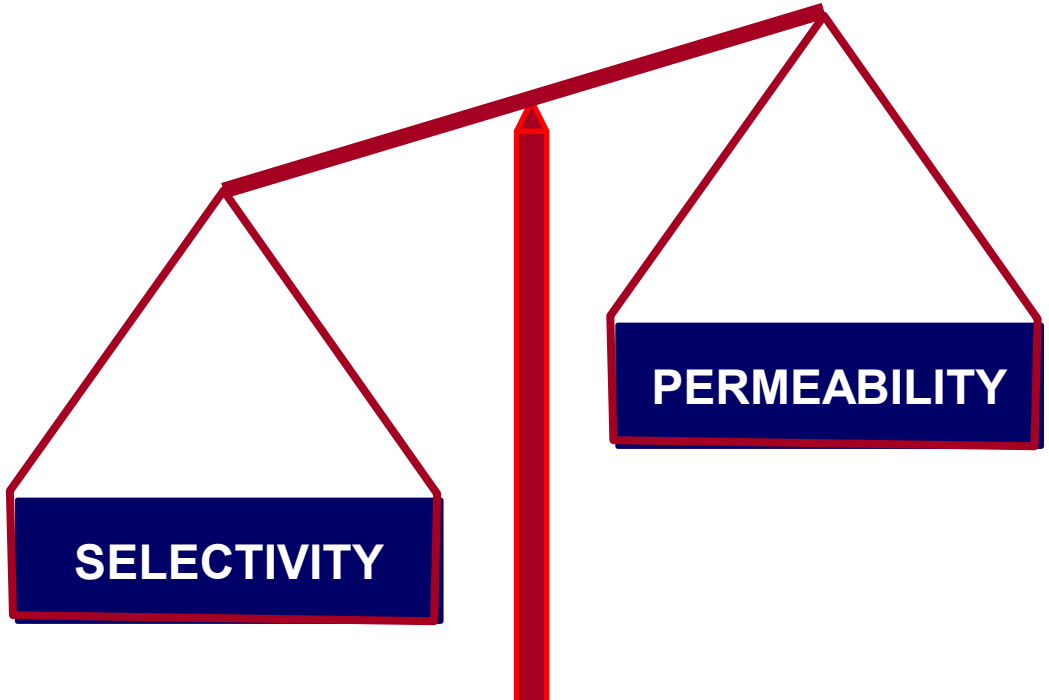


Membrane materials

Requirements

Selectivity

Productivity (permeability, flux)

} Trade-off

Membrane materials

Requirements

Selectivity

Productivity (permeability, flux)

} Trade-off

Processability

Mechanical properties

Chemical / thermal stability

Long-term performance (resistance to ageing, fouling…)

Post-combustion CO_2 capture

Low concentration
10–15% CO_2 in N_2

Large volume
600 MW coal-fired power station produces
~10,000 tonnes CO_2 per day

Low pressure

Post-combustion CO_2 capture

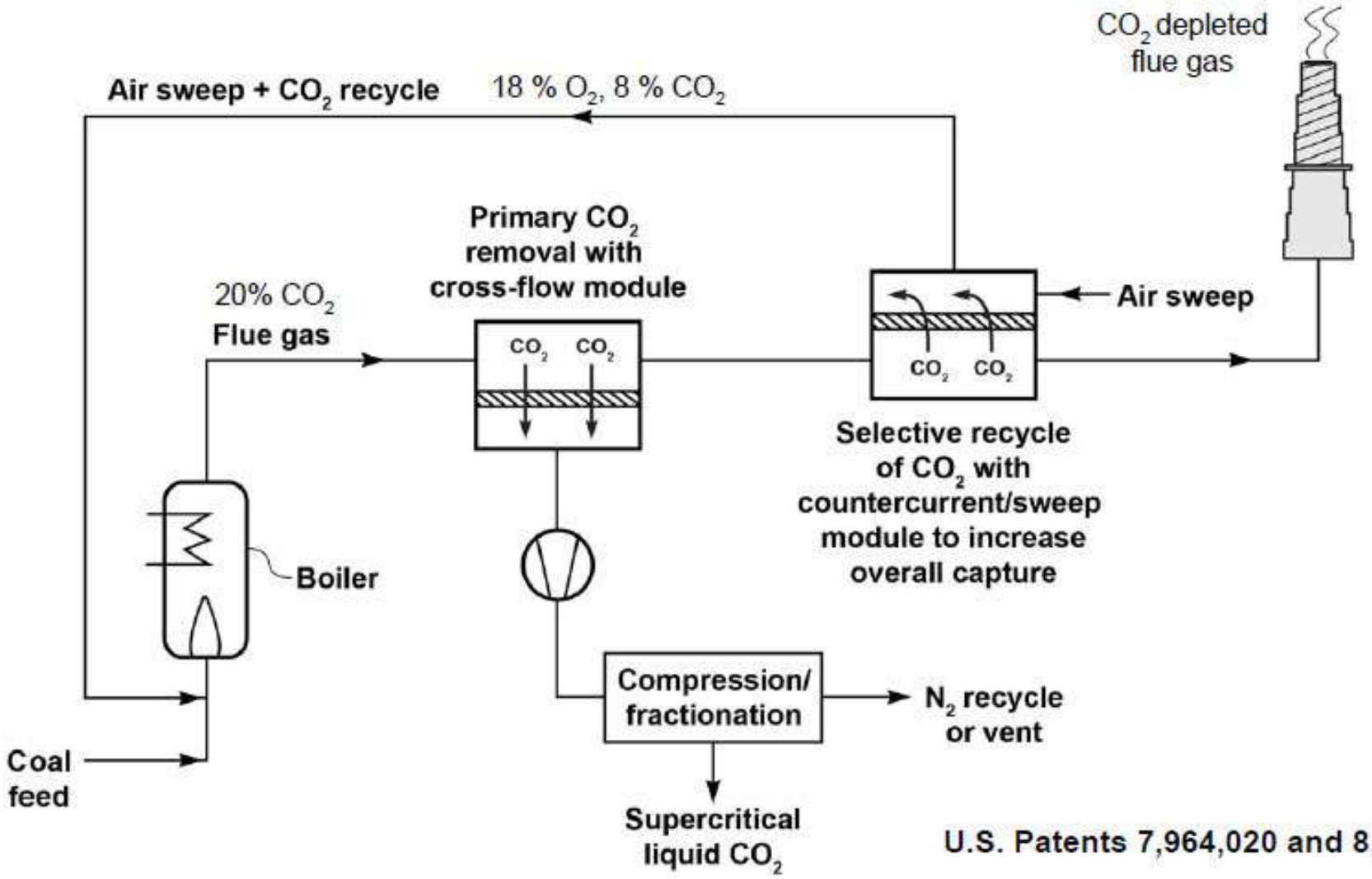
Low concentration
10–15% CO_2 in N_2

Large volume
600 MW coal-fired power station produces
~10,000 tonnes CO_2 per day

Low pressure

Cannot get high purity and high recovery using a single-stage membrane process

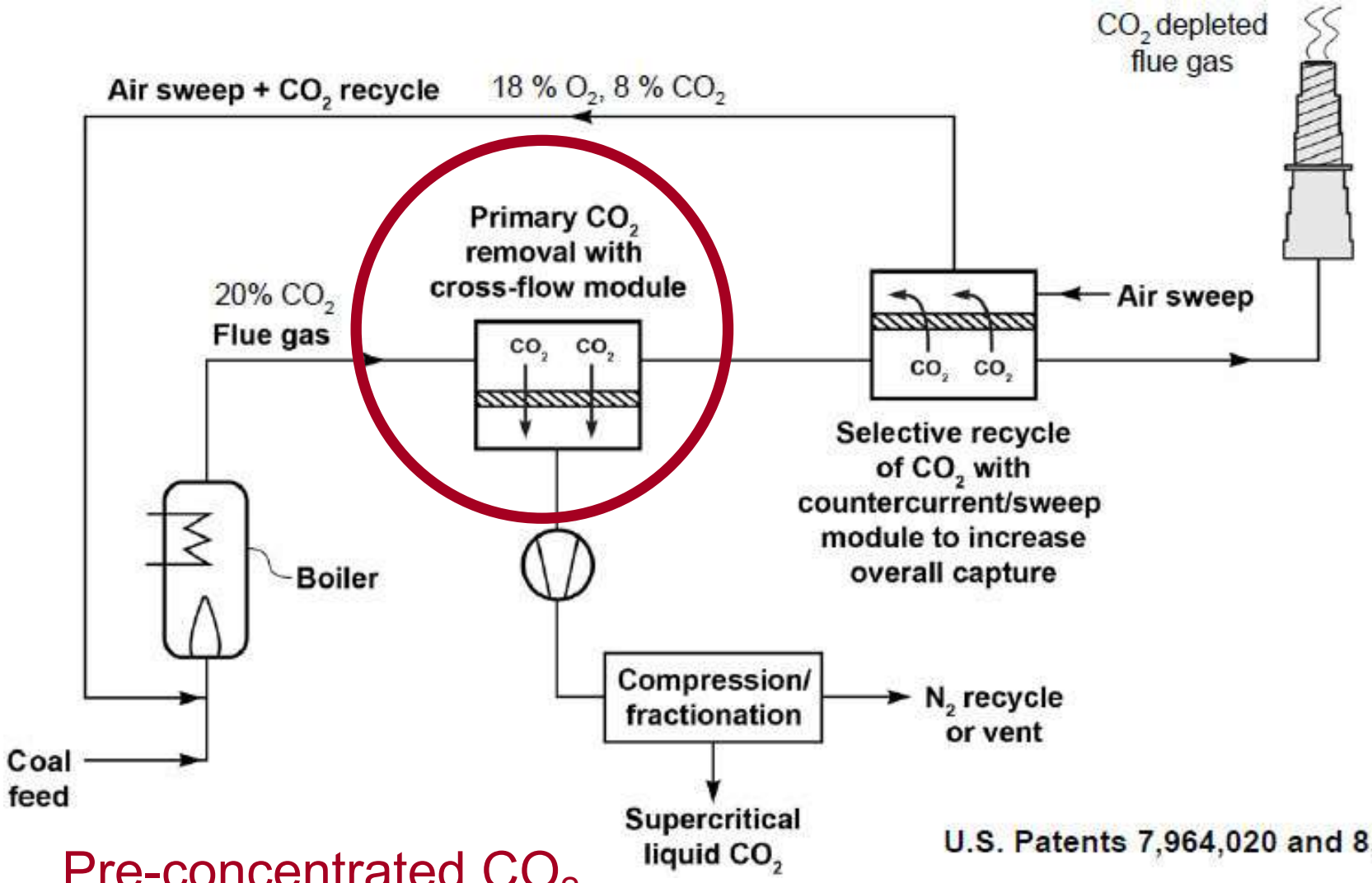
MTR CO_2 capture process



U.S. Patents 7,964,020 and 8,025,715

MTR Membrane Technology & Research

MTR CO_2 capture process

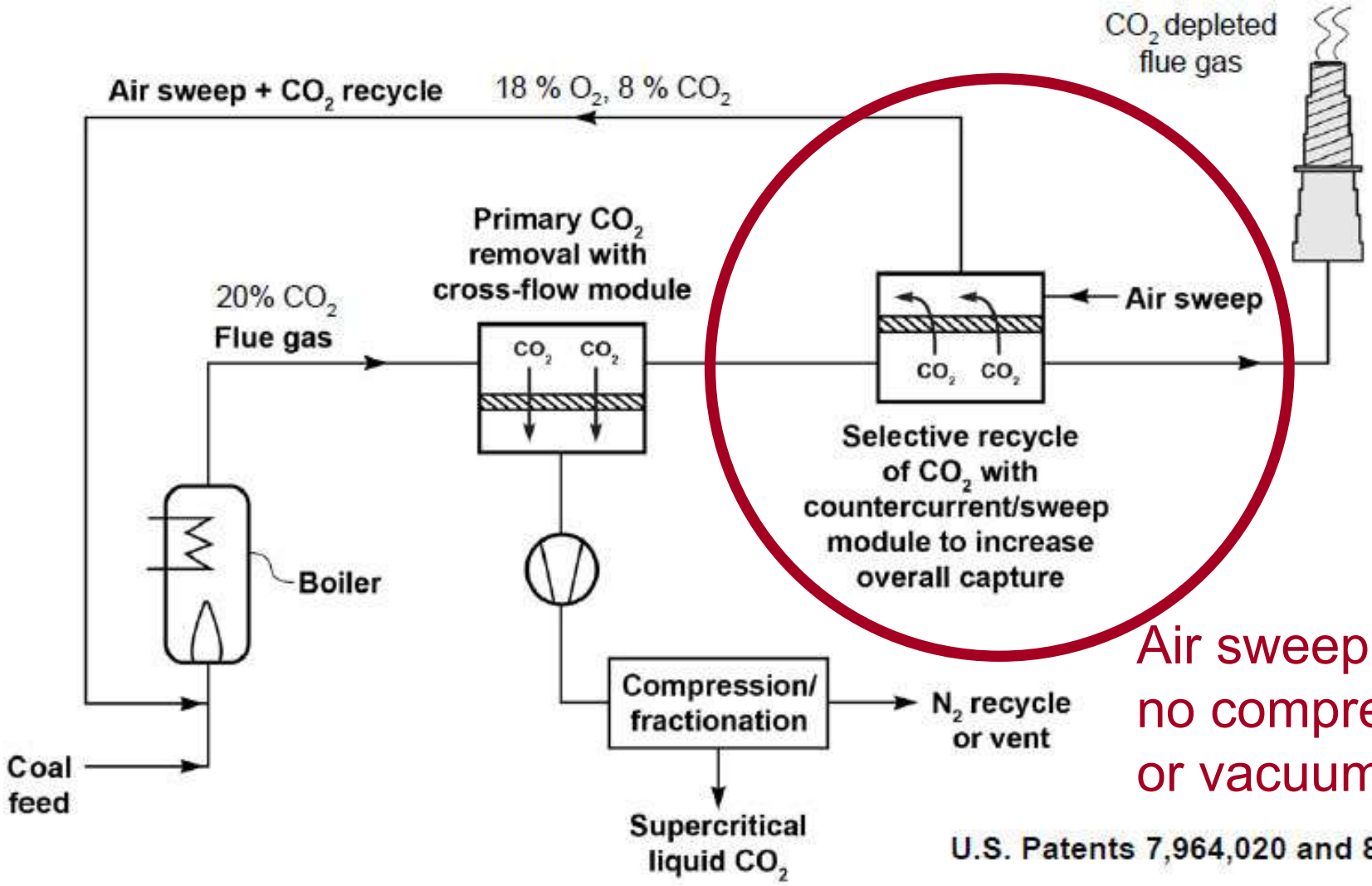


U.S. Patents 7,964,020 and 8,025,715

Pre-concentrated CO_2, reduces membrane area and power

MTR Membrane Technology & Research

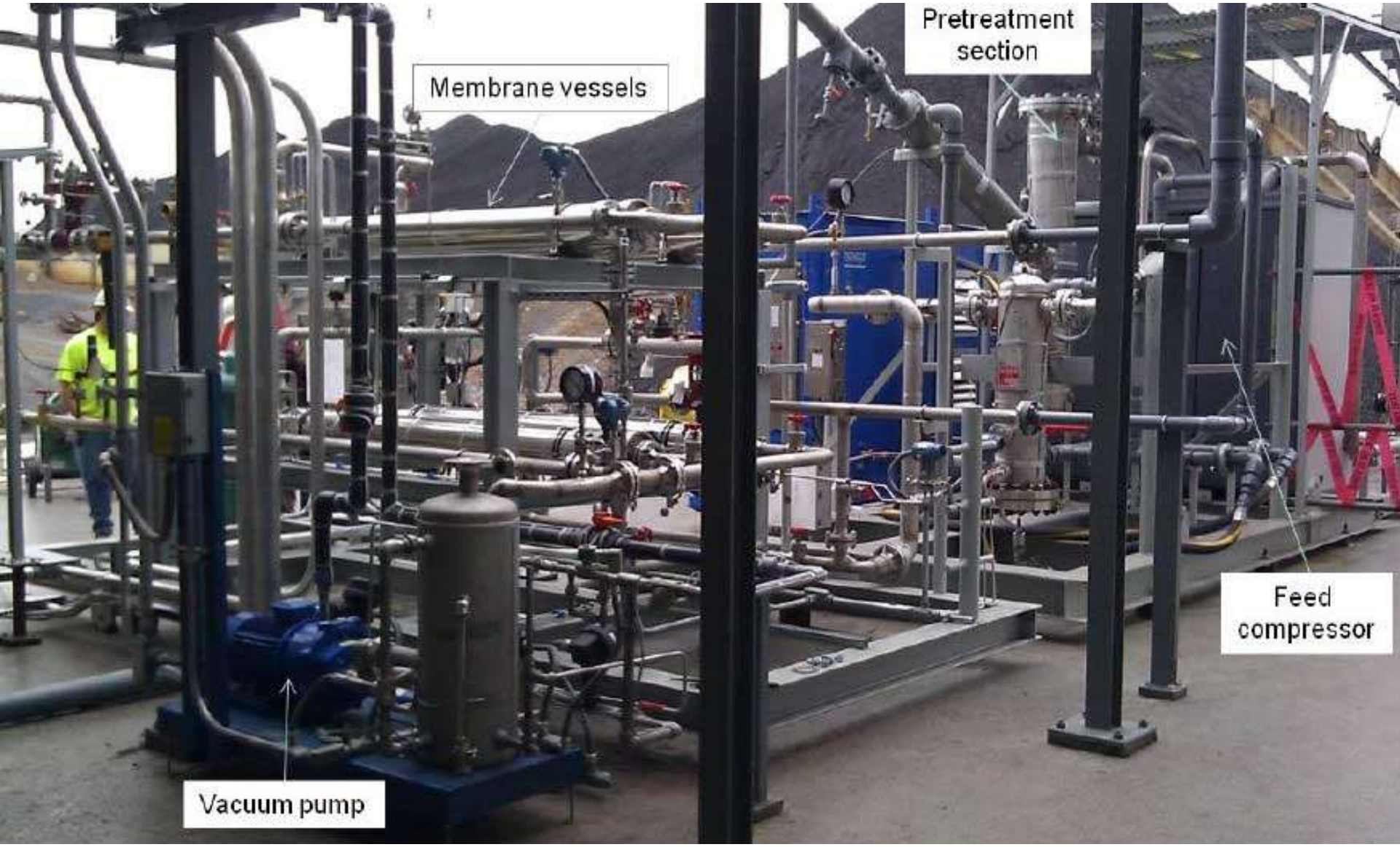
MTR CO_2 capture process



Air sweep, no compression or vacuum

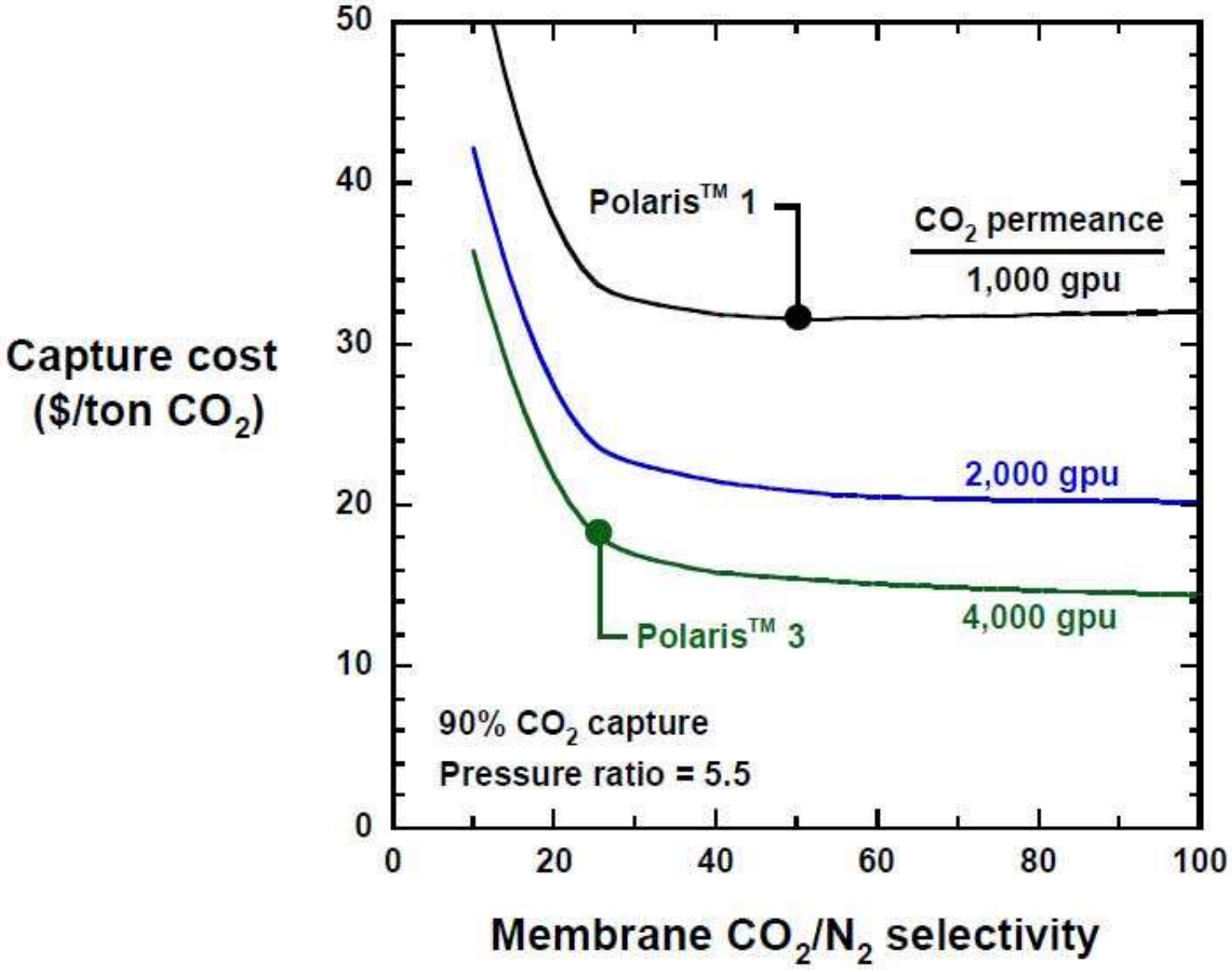
U.S. Patents 7,964,020 and 8,025,715

MTR Membrane Technology & Research



Test system at National Carbon Capture Centre (NCCC)

MTR Membrane Technology & Research



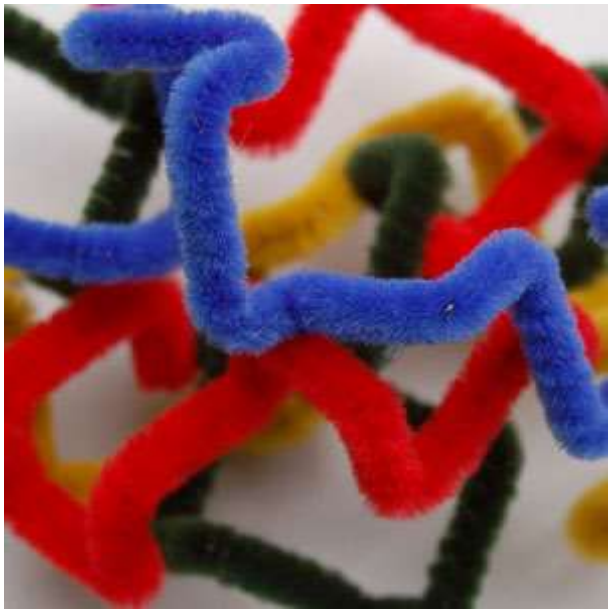
High CO_2 permeance is necessary to reduce cost

MTR Membrane Technology & Research

Polymers of Intrinsic Microporosity

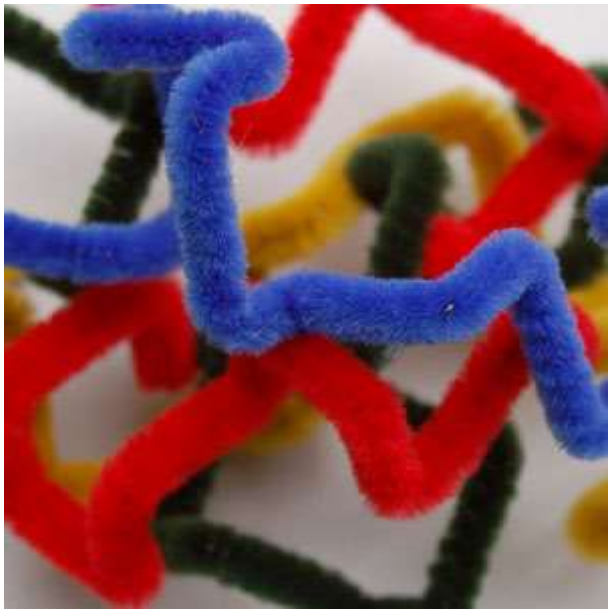
Flexible polymer chains can rearrange

Rigid polymer chains pack together



Rigid, contorted polymer chains cannot fill space

Polymers of Intrinsic Microporosity

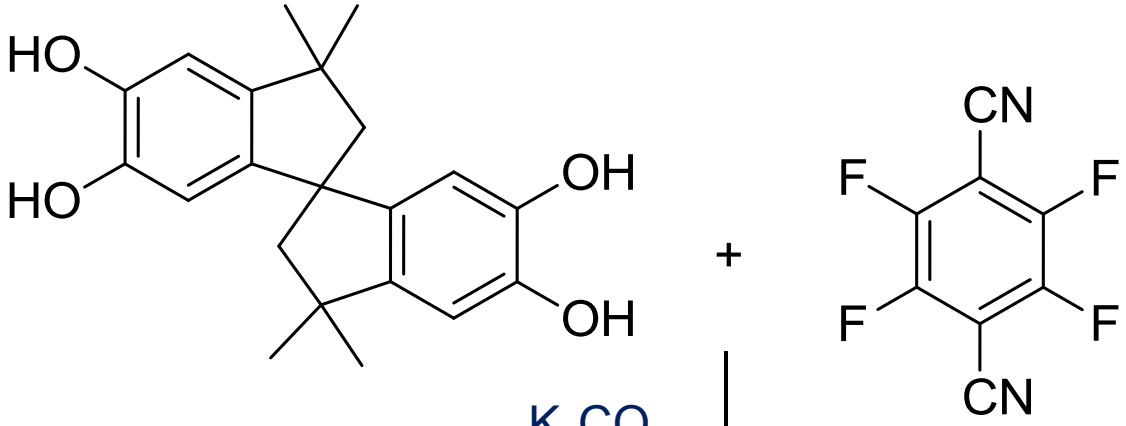


Molecular sieve

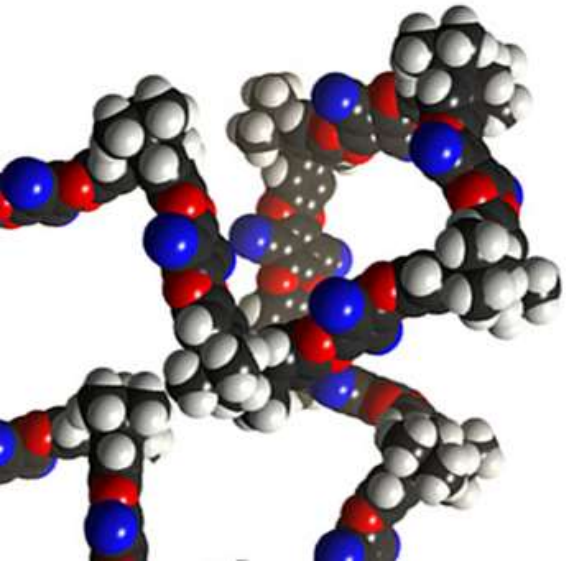
PIM-1

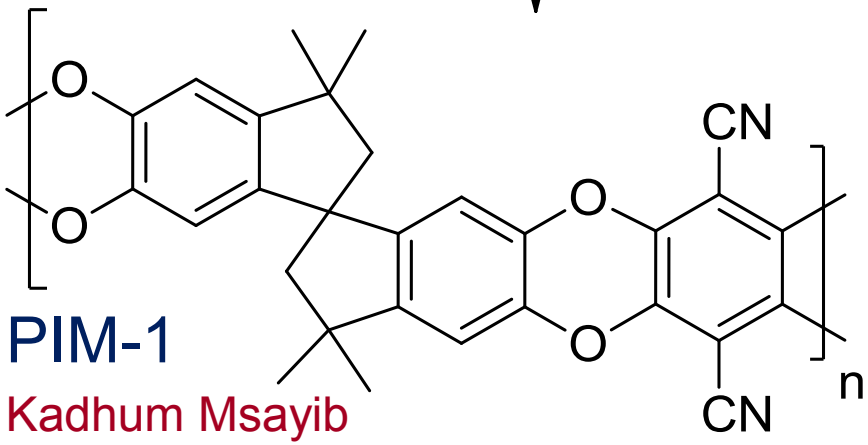
5,5',6,6'-tetrahydroxy-
3,3,3',3'-tetramethyl-
1,1'-spirobisindane

tetrafluoro-
terephthalonitrile



K_2CO_3
dimethylformamide
65 ºC





PIM-1

Kadhum Msayib

P.M. Budd *et al.*, *Chem. Commun.*, 2004, 230.

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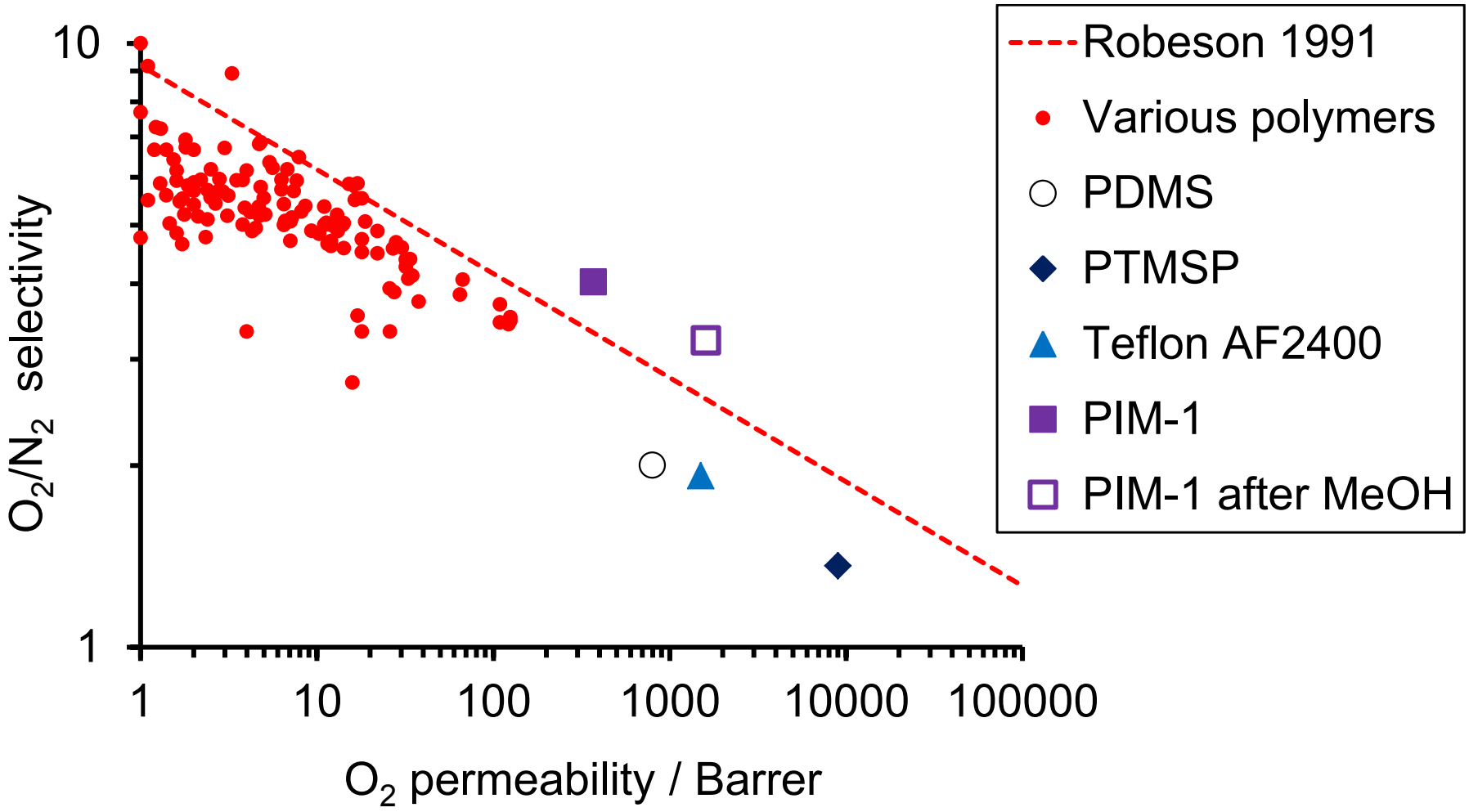
Gas separation



P.M. Budd *et al.*,
J. Membr Sci., 2005, **252**, 263; 2008, **325**, 851.

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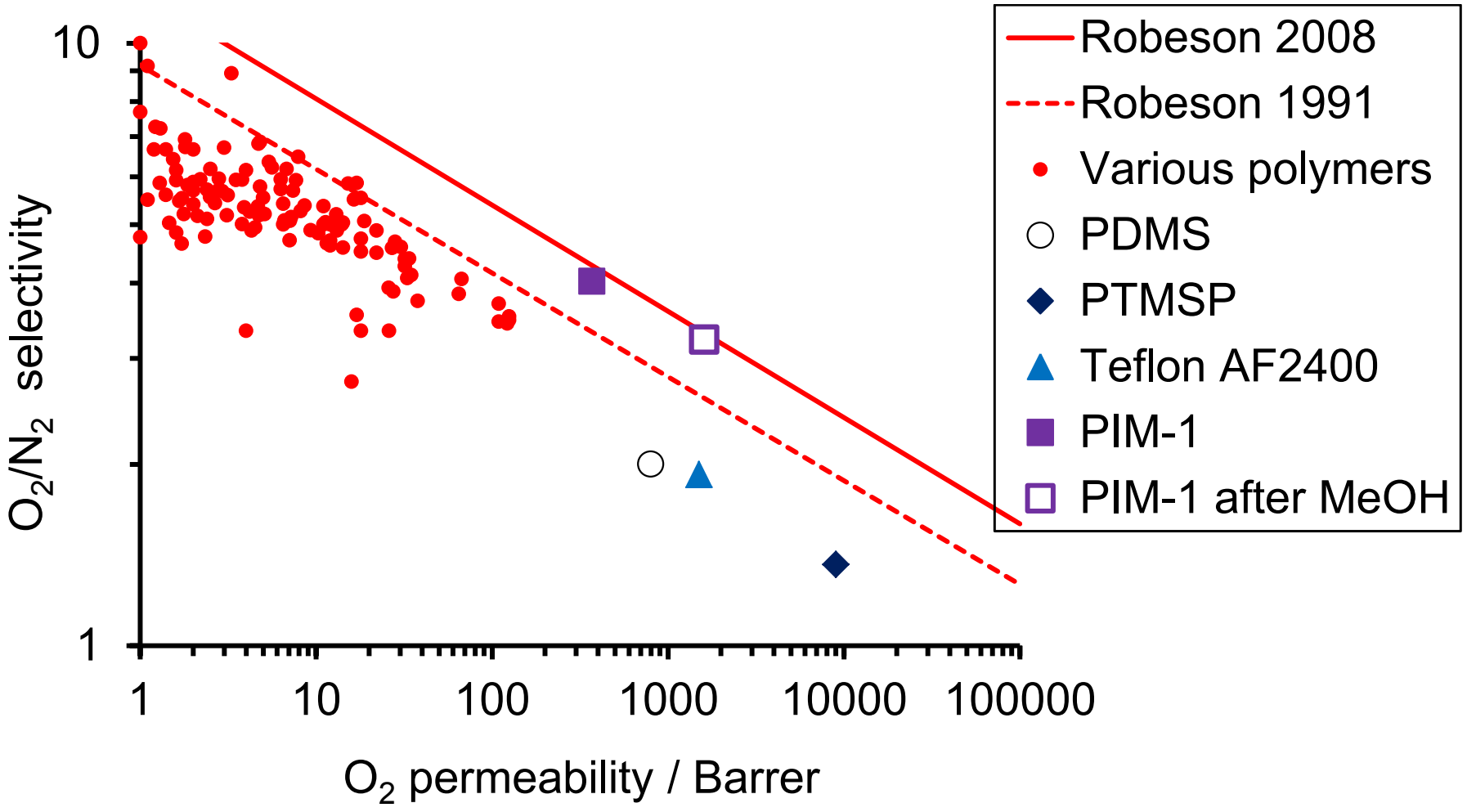

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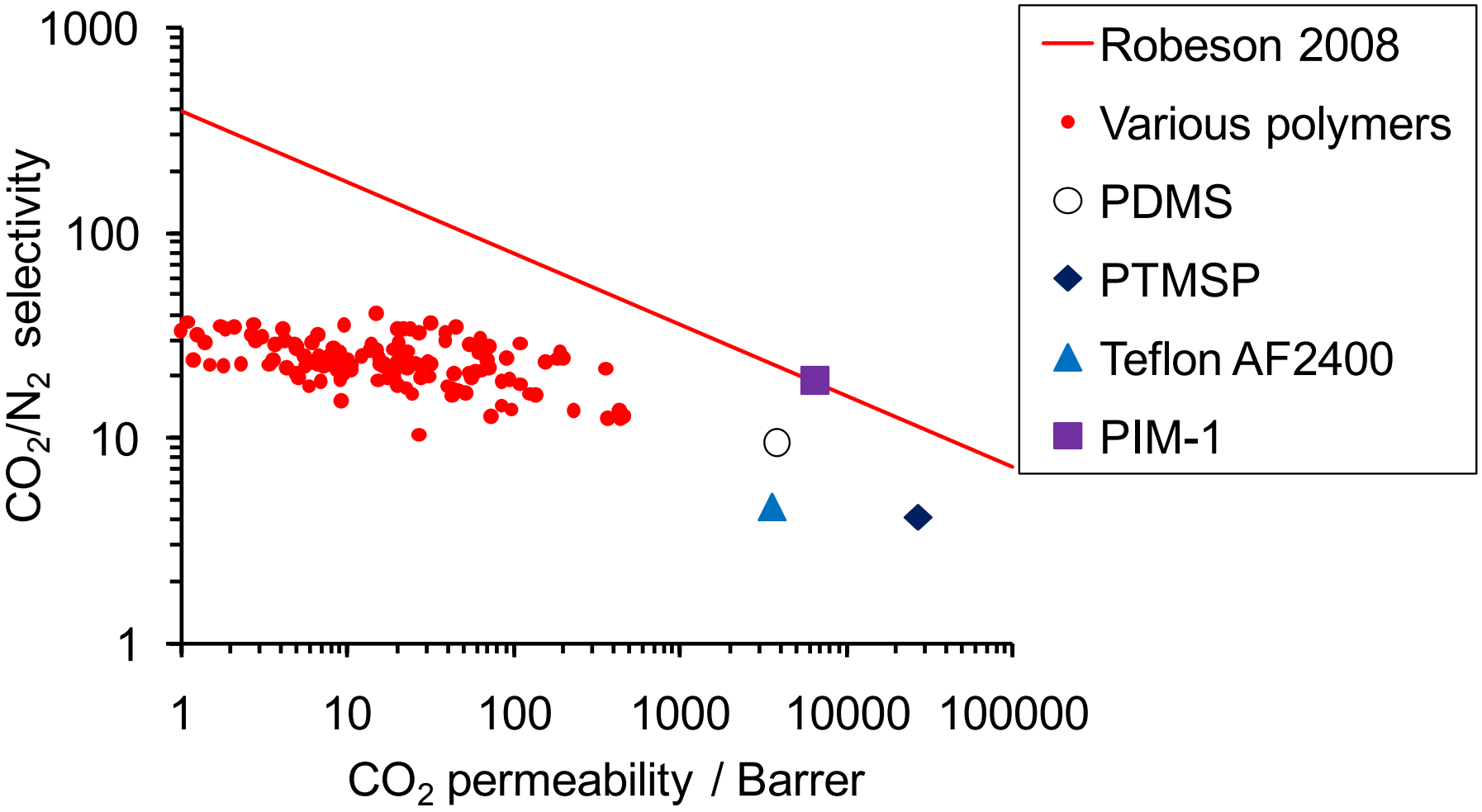

P.M. Budd *et al.*,
J. Membr Sci., 2005, **252**, 263; 2008, **325**, 851.

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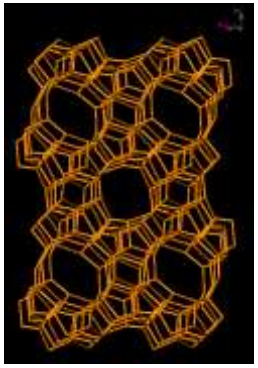
Mixed matrix membranes

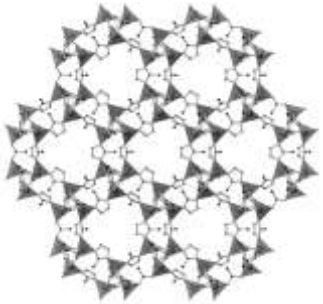
PIM-1
+

Inorganic porous materials



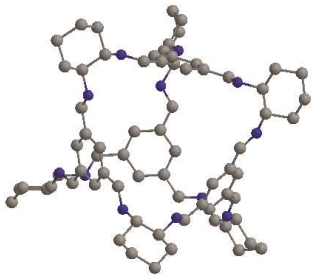
Silicalite
C.R. Mason *et al.*, *Polymer*, 2013, **54**, 2222.
Uni. Manchester
Uni. Calabria
ITM-CNR
ICT Prague

Metal-organic frameworks



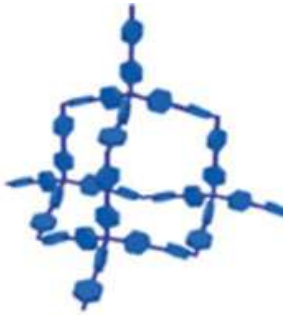
ZIF-8
A.F. Bushell *et al.*, *J. Membr. Sci.*, 2013, **427**, 48.
Uni. Manchester
TIPS-RAS
ITM-CNR
ICT Prague

Organic cage molecules



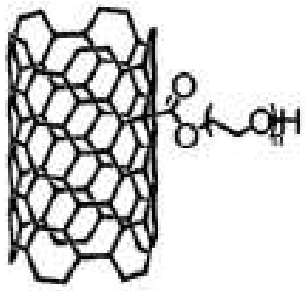
Cage-3
A.F. Bushell *et al.*, *Angew. Chem. Int. Edn.*, 2013, **52**, 1253.
Uni. Manchester
Uni. Liverpool
ITM-CNR

Organic polymer frameworks



PAF-1
C.H. Lau *et al.*, *Angew. Chem. Int. Edn.*, 2014, **53**, 5322.
CSIRO
Uni. Colorado
Monash Uni.

Carbons



Nanotubes
M.M.Khan *et al.*, *J. Membr. Sci.* 2013, **436**, 109.
HZG

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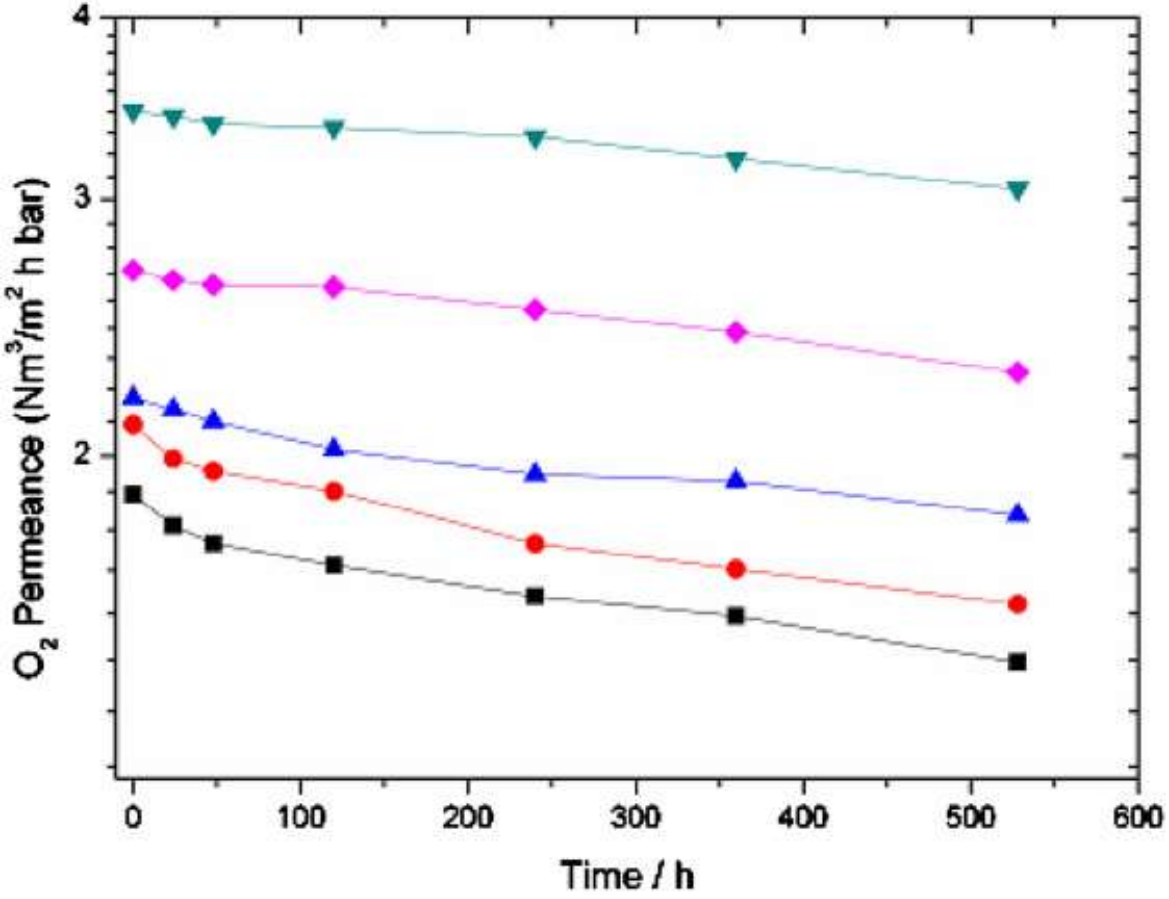
PIM-1 / carbon nanotubes

Helmholtz-Zentrum Geesthacht

M. Khan *et al.*, *Nanoscale Res. Lett.*, 2012, **7**, 504.

MWCNTs functionalised with PEG



2 wt% f-MWCNTs

3 wt% f-MWCNTs

1 wt% f-MWCNTs

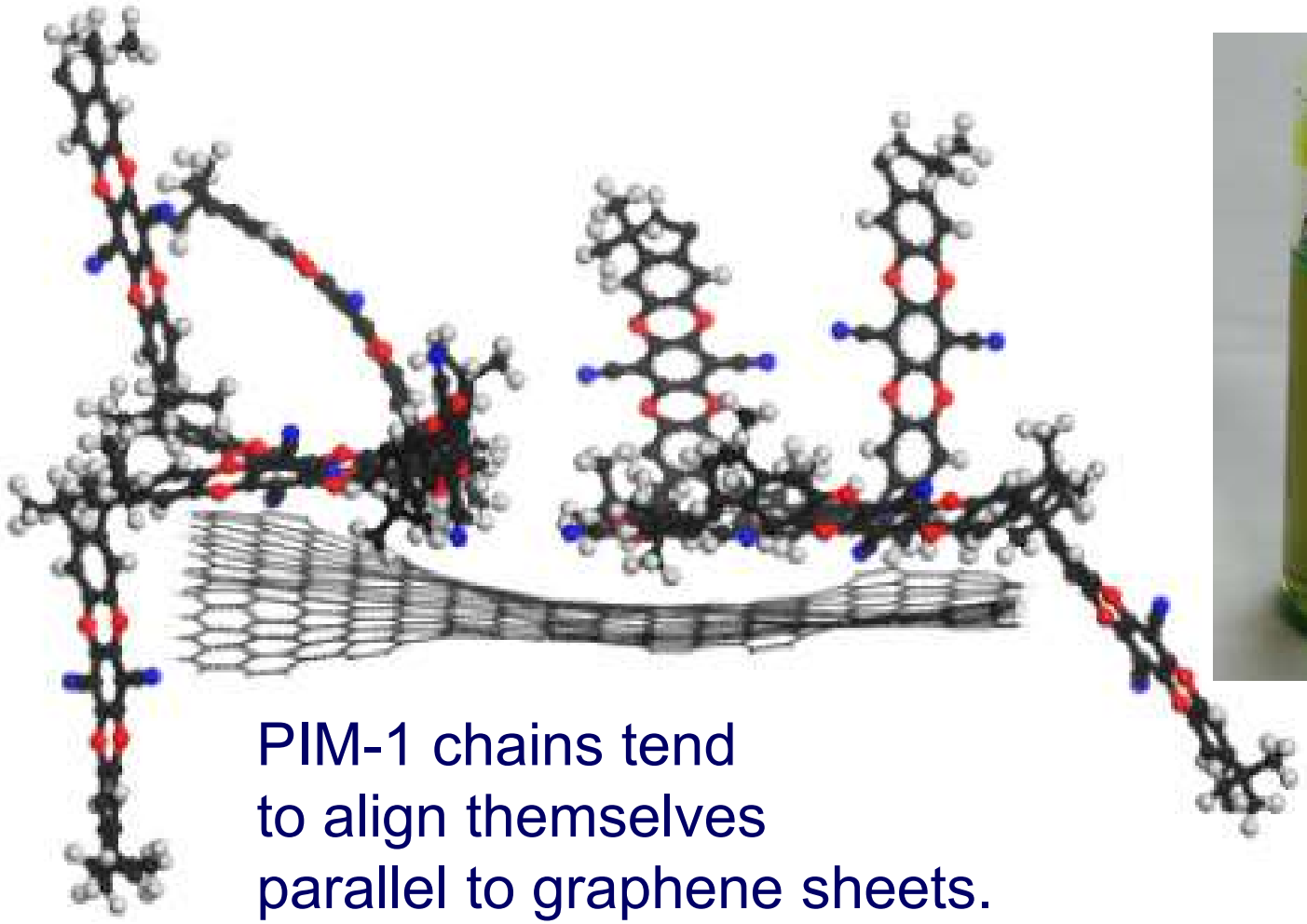
0.5 wt% f-MWCNTs

PIM-1

Helmholtz-Zentrum Geesthacht

Zentrum für Material- und Küstenforschung

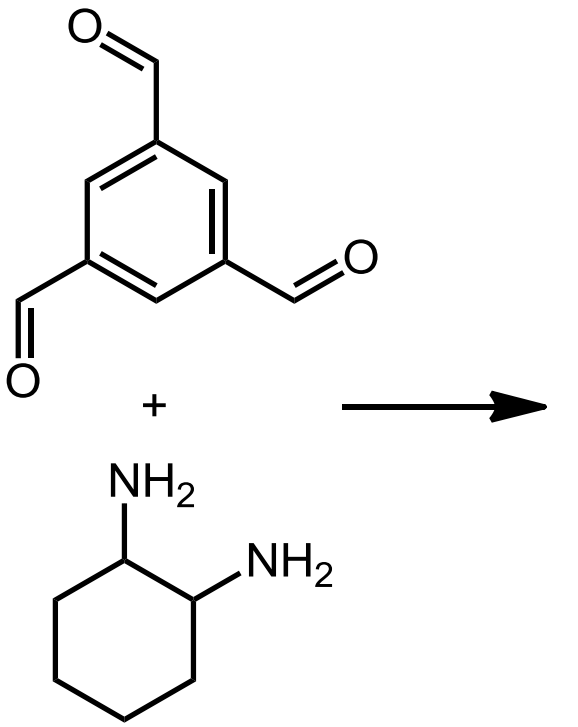
PIM-1 / graphene

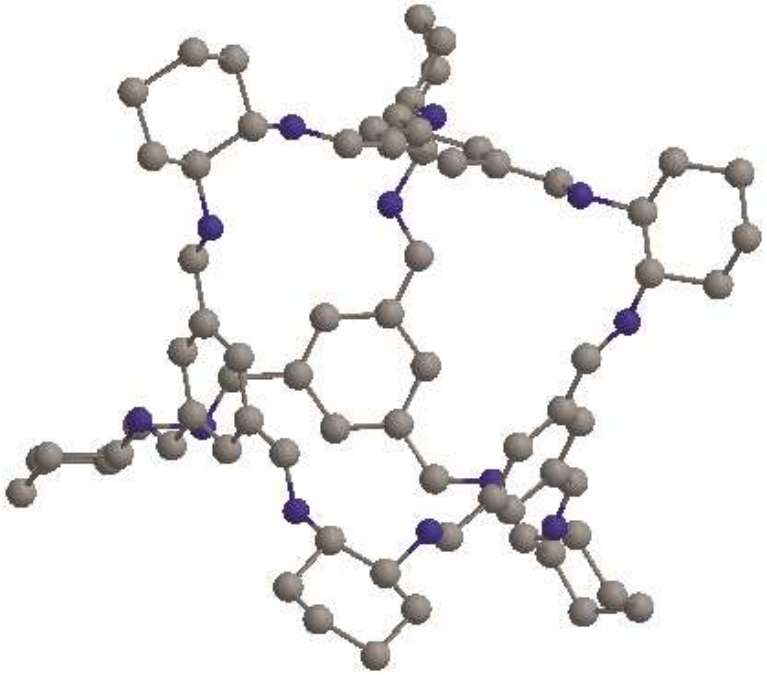


PIM-1 chains tend
to align themselves
parallel to graphene sheets.

A. Gonciaruk *et al.*,
Micropor. Mesopor. Mater., 2015, **209**, 126.

PIM-1 / cage CC3





CC3 windows *ca*. 0.6 nm

T. Tozawa *et al.*, *Nat. Mater.*, 2009, **8**, 973.
J.T.A. Jones *et al.*, *Nature*, 2011, **474**, 367.

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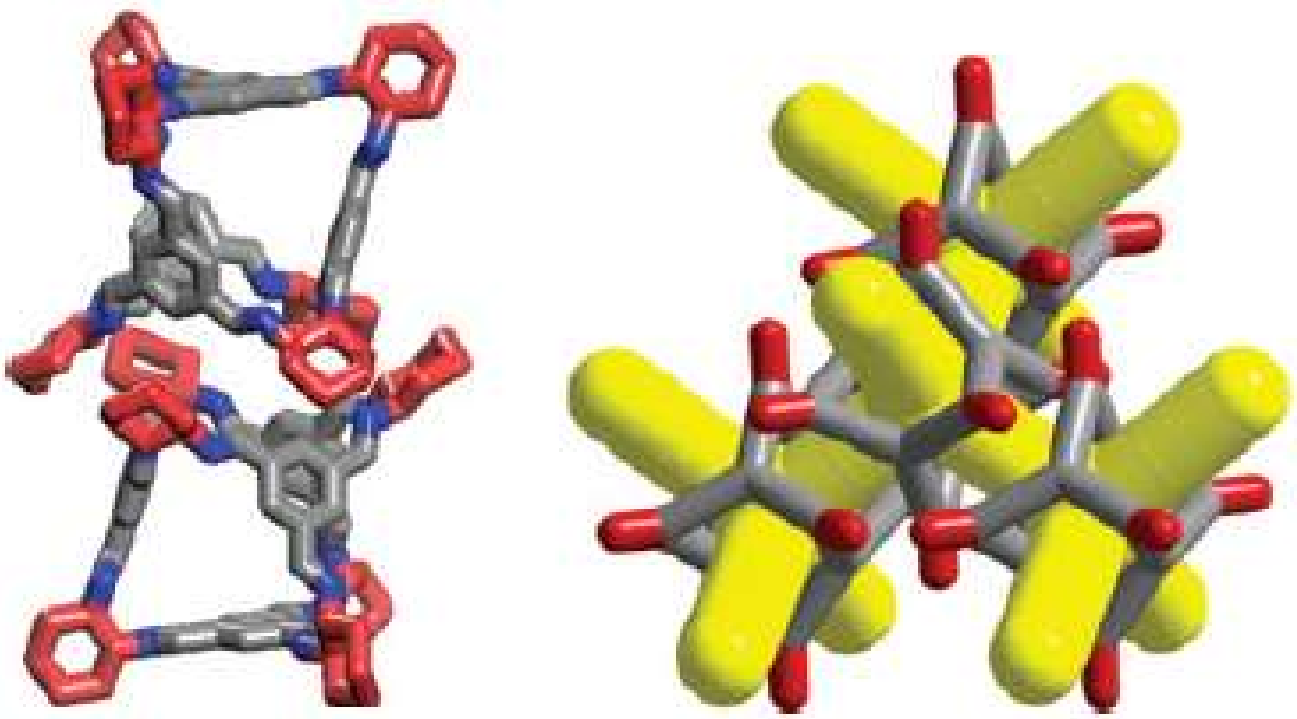
PIM-1 / cage CC3



CC3 packs window to window in crystal structure, generating an interconnected pore network.

T. Tozawa *et al.*, *Nat. Mater.*, 2009, **8**, 973.
J.T.A. Jones *et al.*, *Nature*, 2011, **474**, 367.

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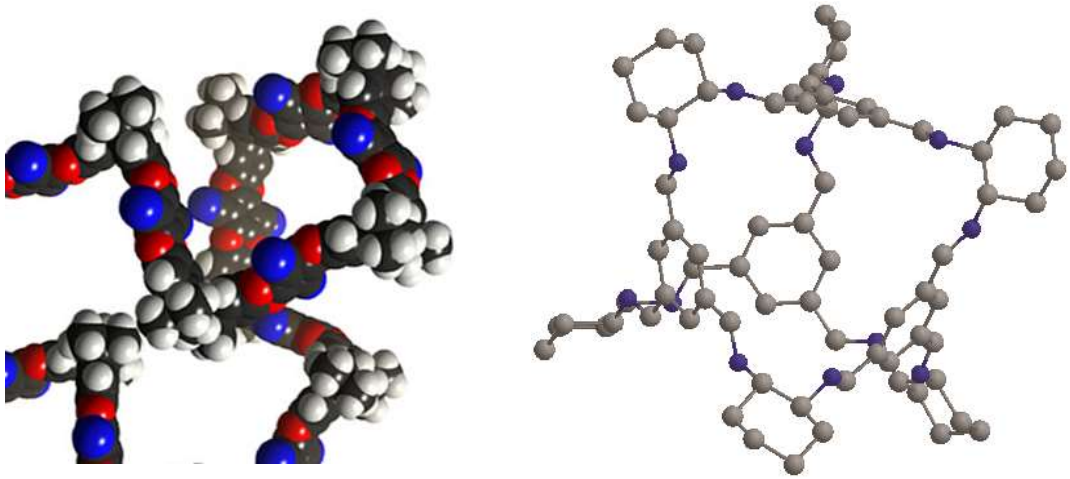
PIM-1 / cage CC3

A. Bushell *et al.*, *Angew. Chem. Int. Ed.*, 2013, **52**, 1253.



(1) In-situ crystallization of porous imine cage-3R (CC3) from molecular solution.

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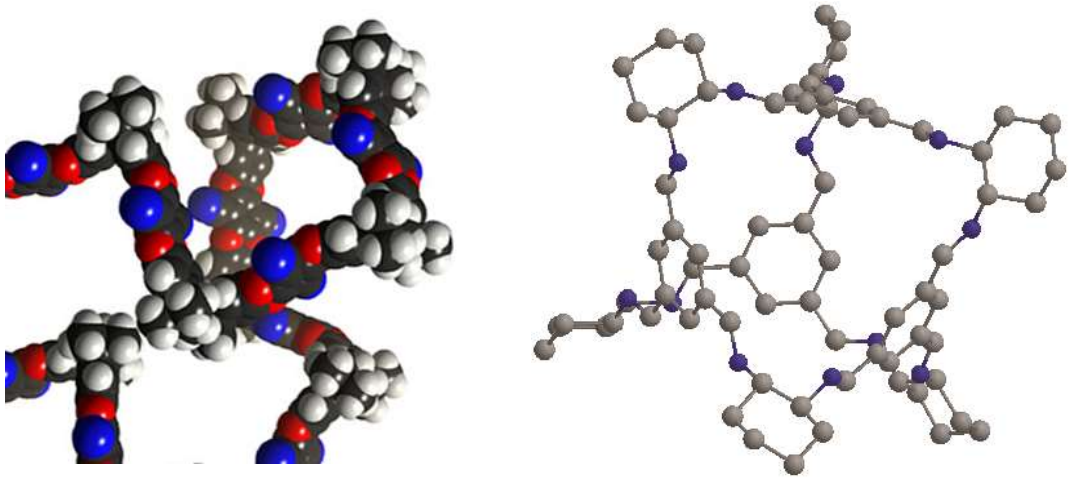

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(2) Dispersion of preformed racemic CC3 nanocrystals (nanoCC3).

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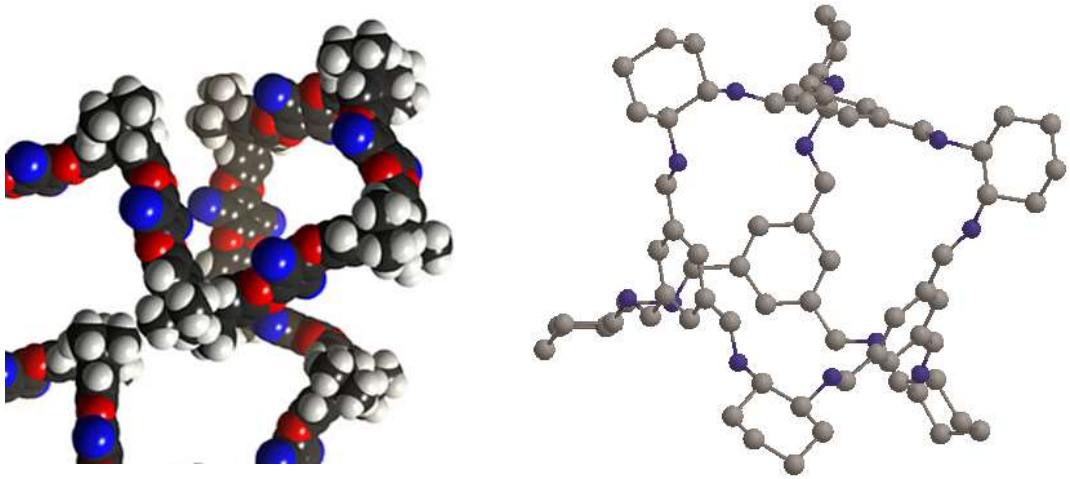

(1) In-situ crystallization of porous imine cage-3R (CC3) from molecular solution.

(2) Dispersion of preformed racemic CC3 nanocrystals (nanoCC3).

(3) Reduced, non-porous amine form of CC3 (redCC3).

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PIM-1 / cage CC3

A. Bushell *et al.*, *Angew. Chem. Int. Ed.*, 2013, **52**, 1253.

PIM-1/CC3

PIM-1/nanoCC3

PIM-1/redCC3

wt. ratio 10:2
wt. fraction 0.17

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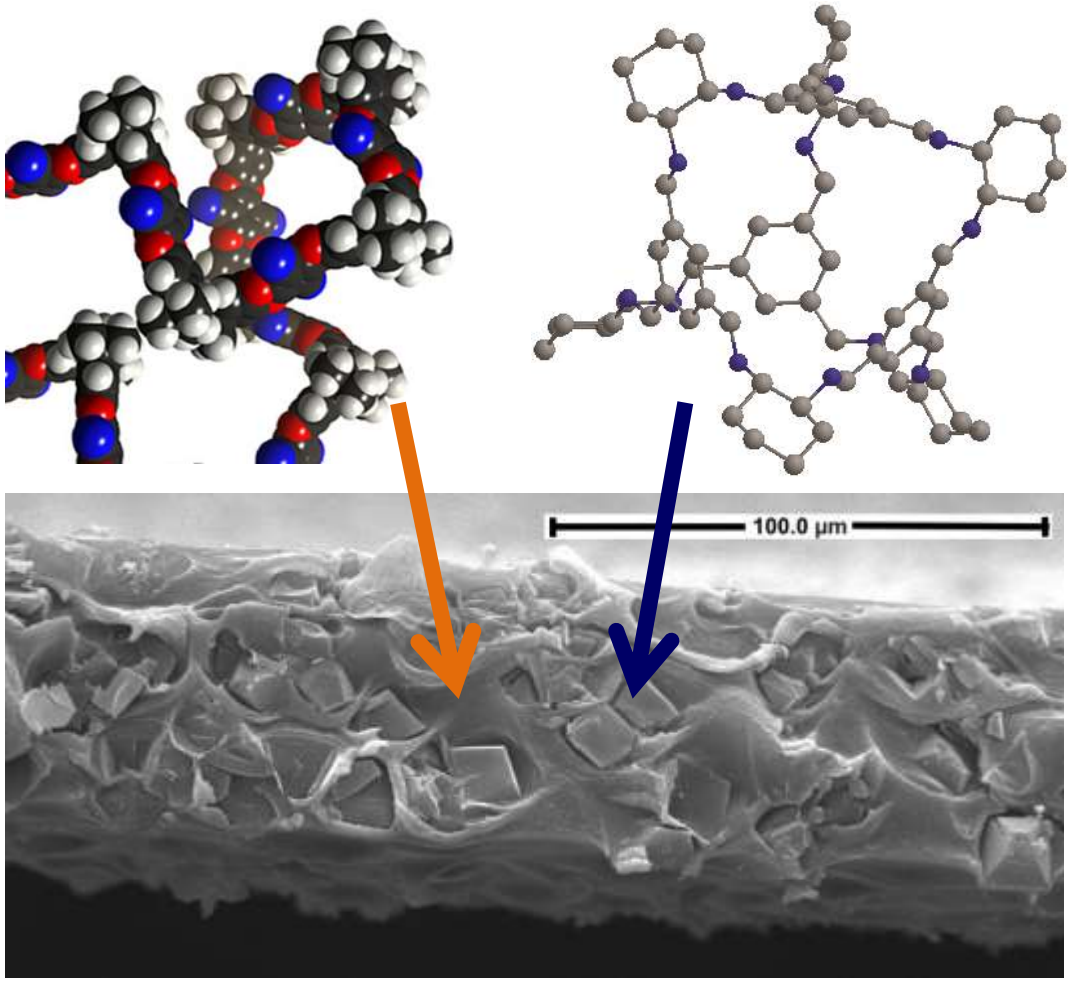

In-situ crystallization

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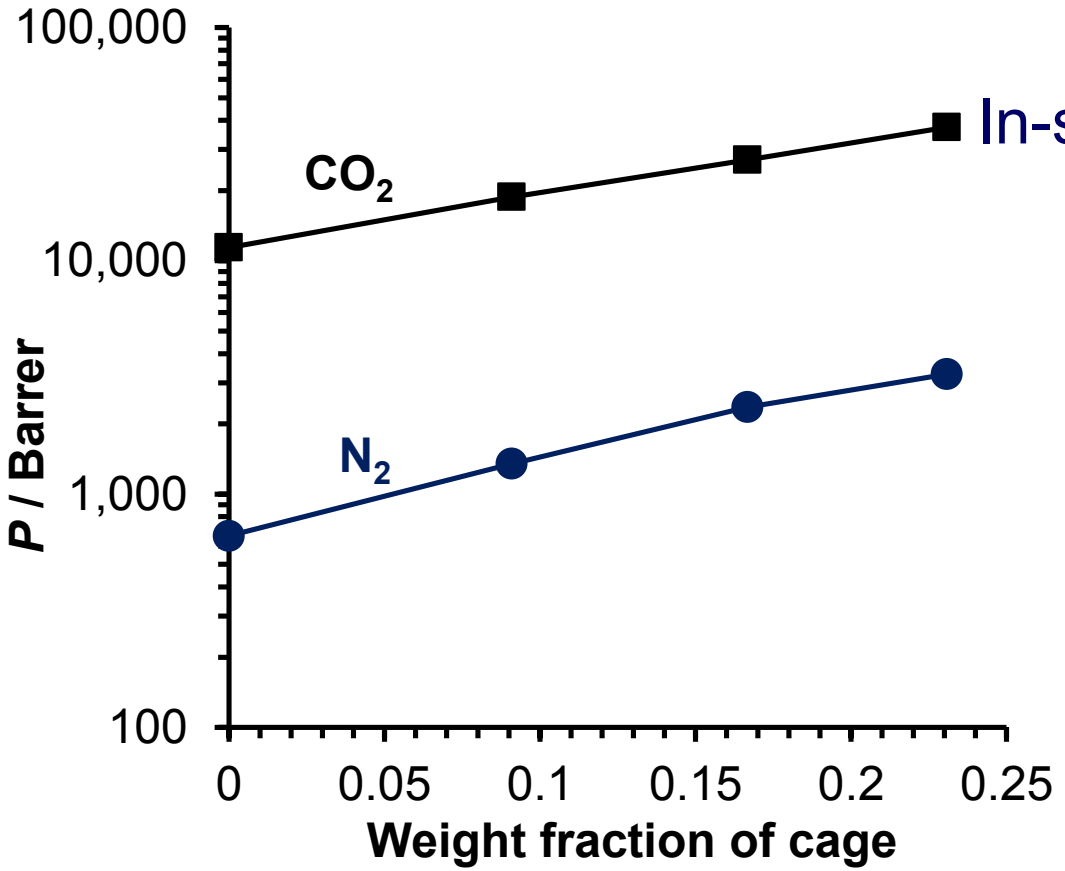

In-situ crystallization

Ethanol-treated membranes

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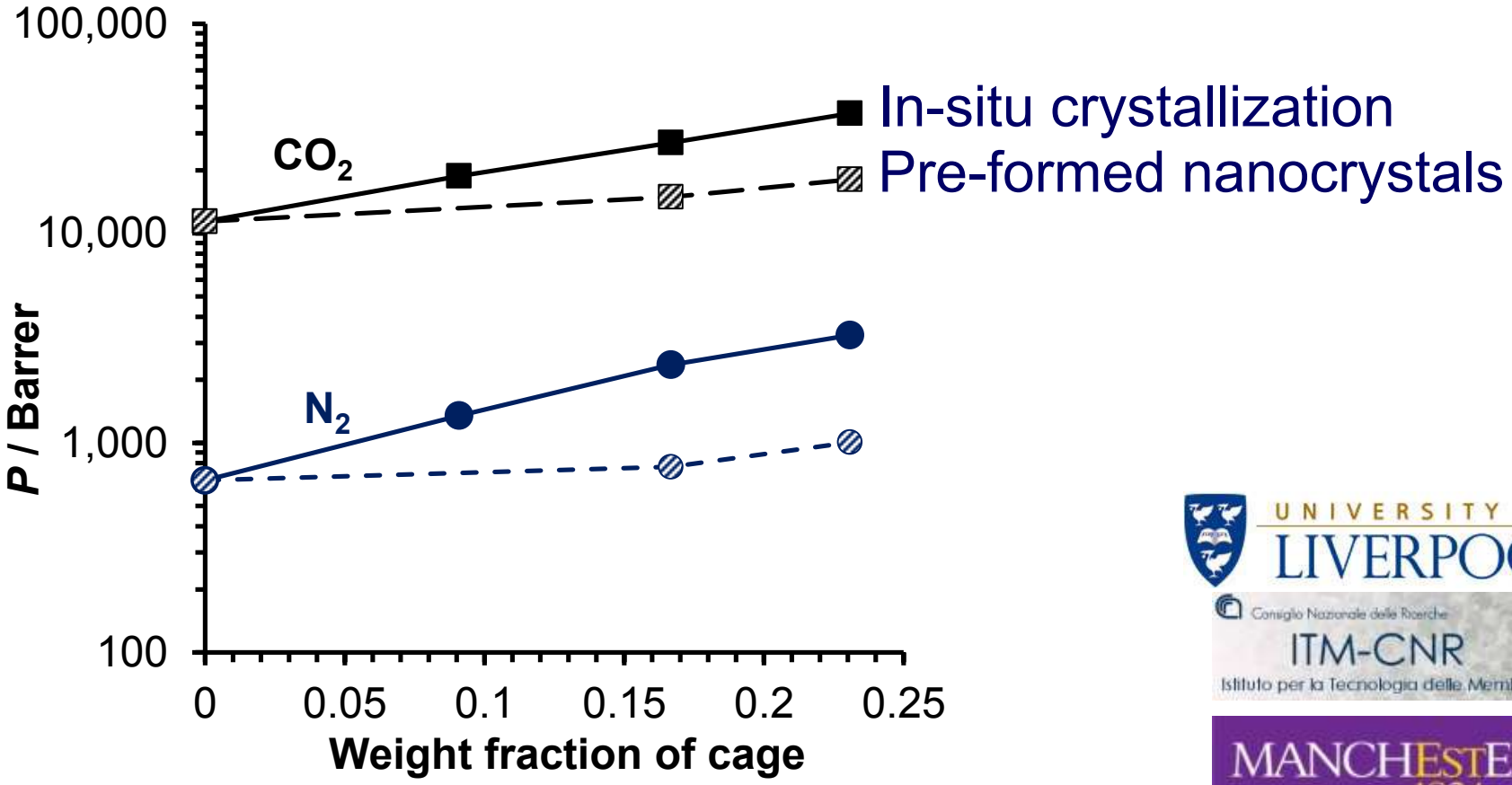
PIM-1 / cage CC3

A. Bushell *et al.*, *Angew. Chem. Int. Ed.*, 2013, **52**, 1253.



Ethanol-treated membranes

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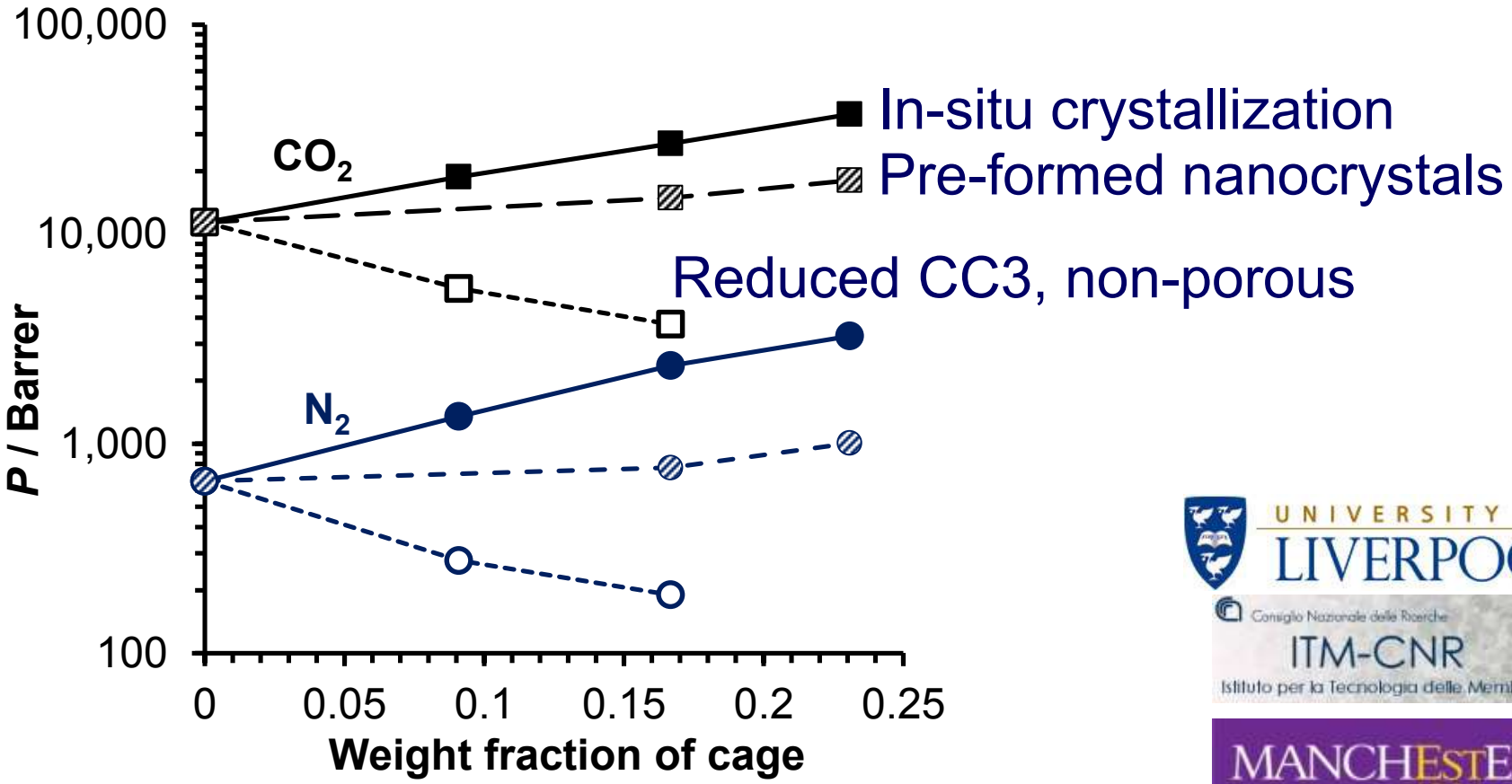
PIM-1 / cage CC3

A. Bushell *et al.*, *Angew. Chem. Int. Ed.*, 2013, **52**, 1253.



Ethanol-treated membranes

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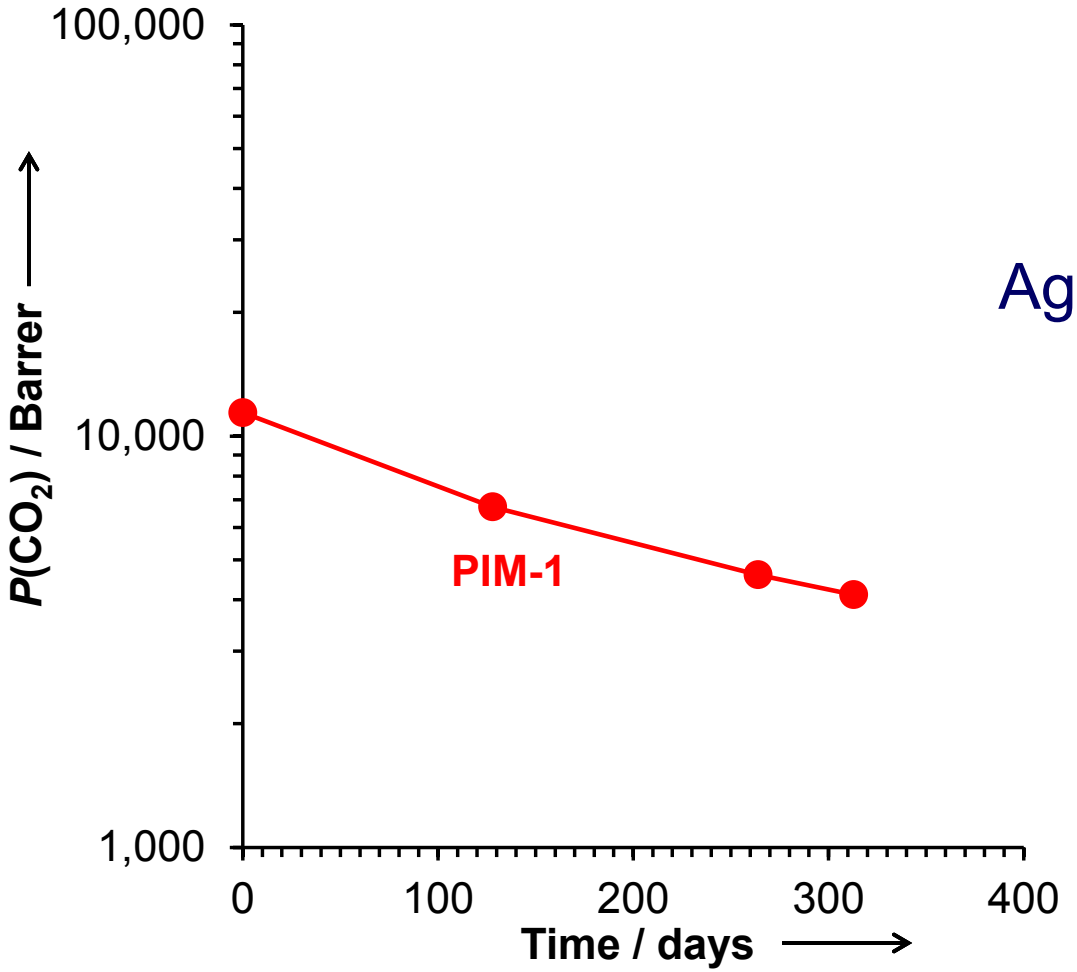

Ageing

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PIM-1 / cage CC3

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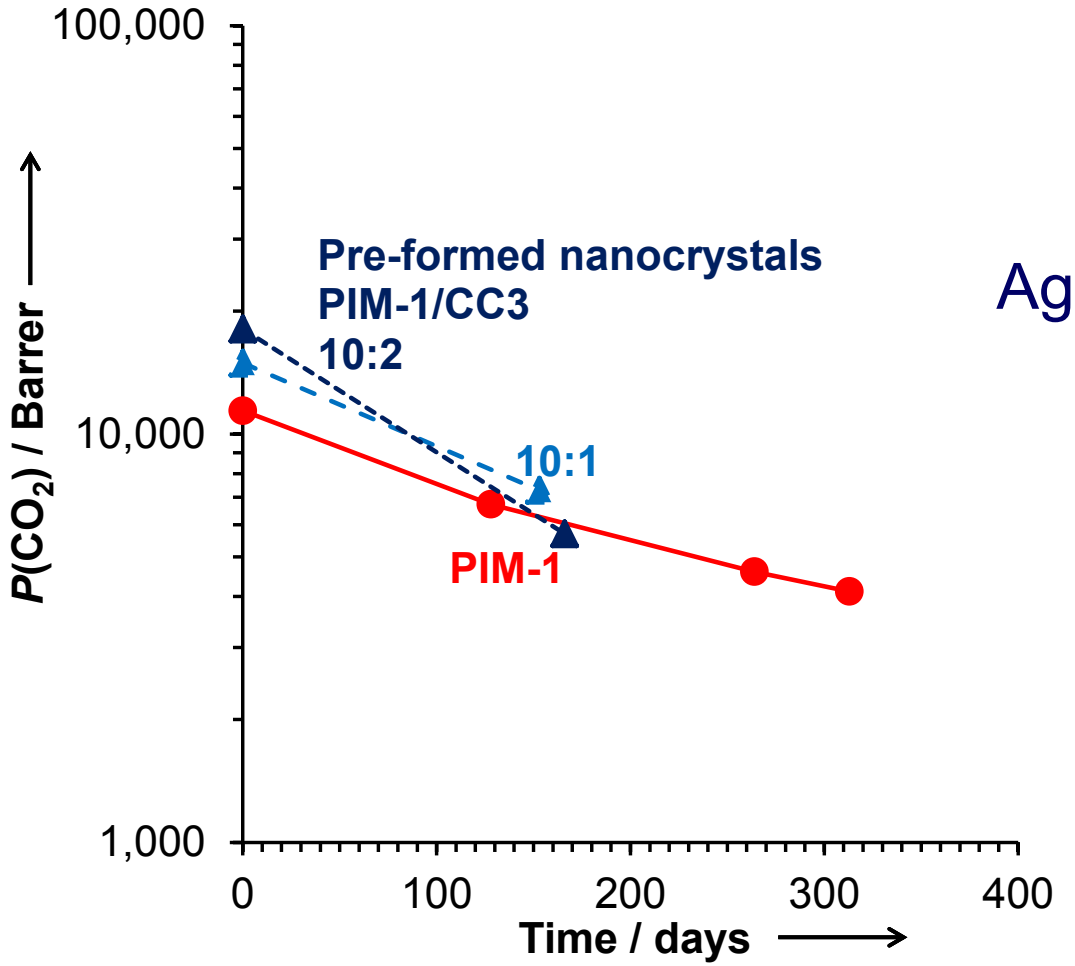

Ageing

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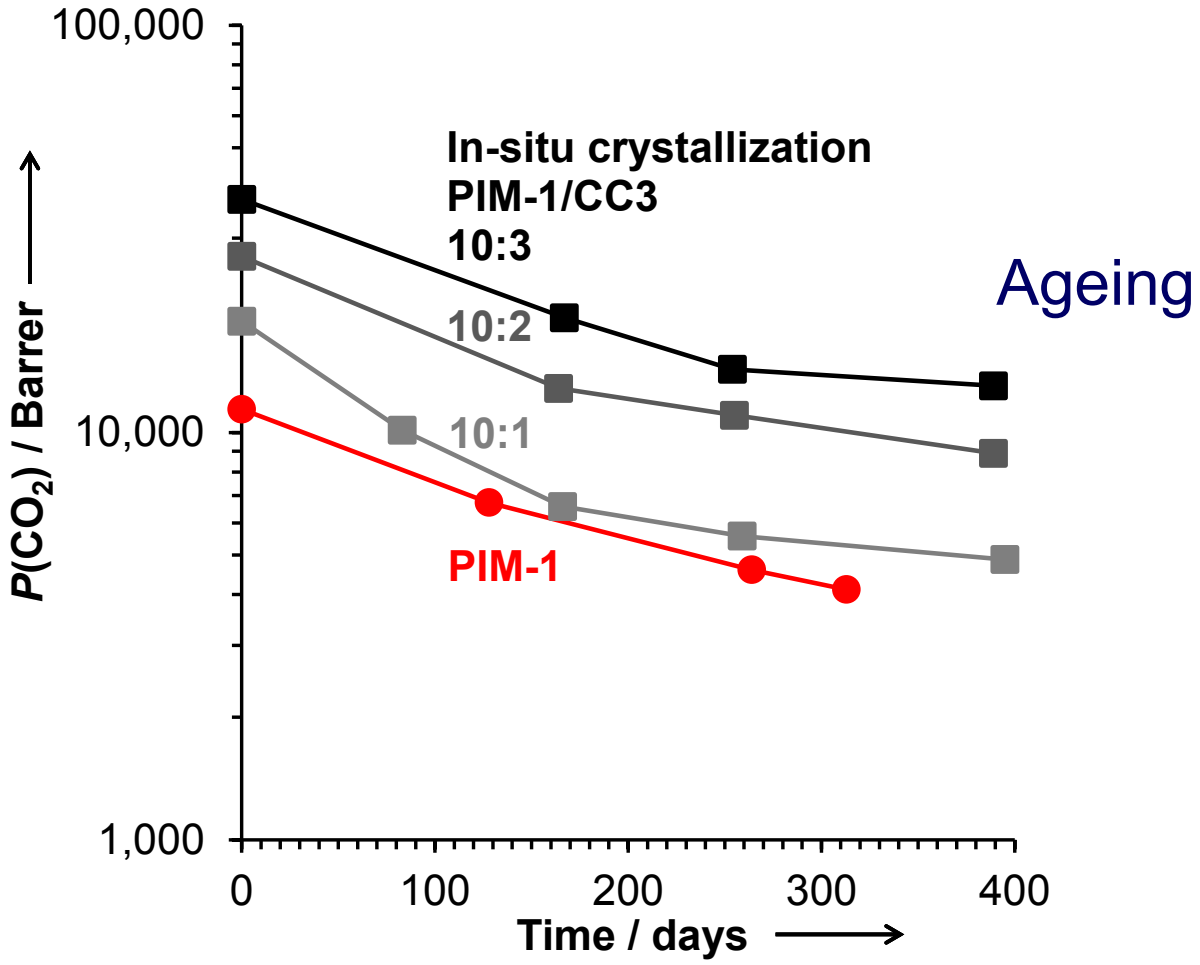

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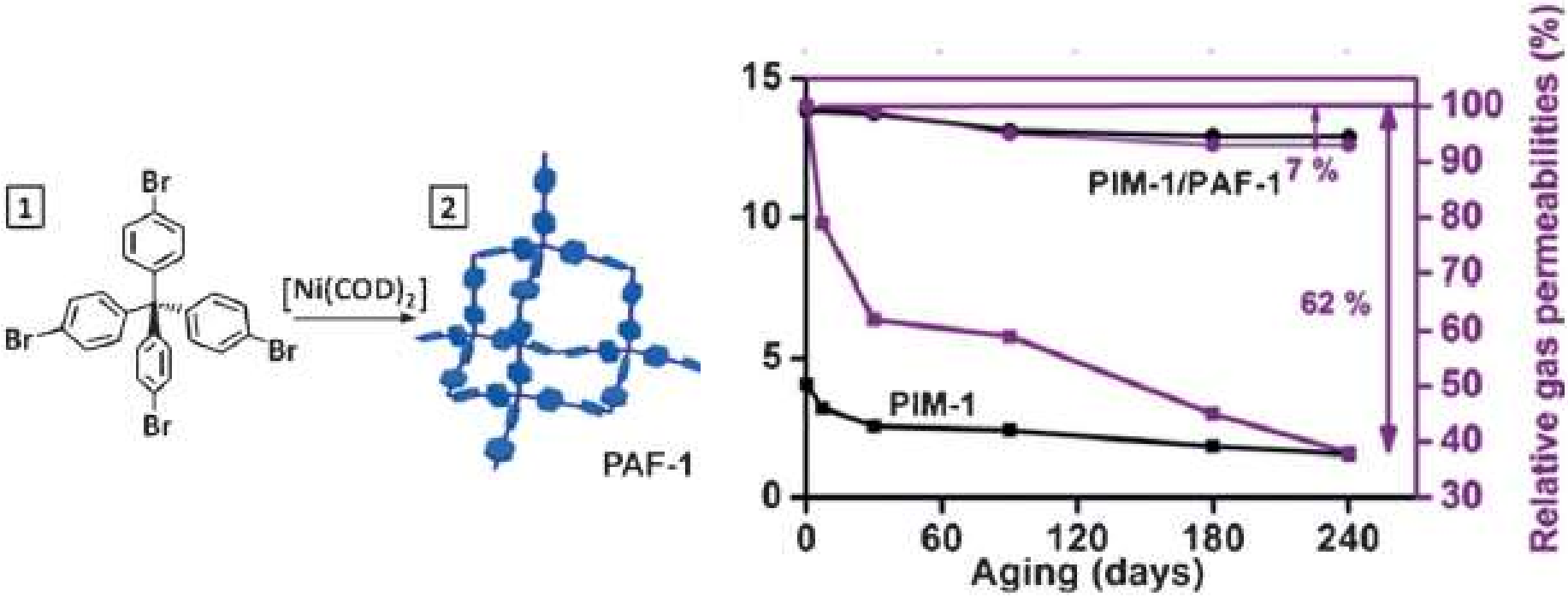
PIM-1 / PAF-1

C.H. Lau *et al*., *Angew. Chem. Int. Ed.*, 2014, **53**, 5322.
CSIRO Division of Materials Science and Engineering;
University of Colorado; Monash University; Australian National University



“Ending aging” in super glassy polymer membranes

Acknowledgements

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Bann Dawood
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Louise Maynard-Atem
Hosna Shamsipour

Martin Attfield

Flor Siperstein
Aleksandra Gonkiaruk
Annalaura del Regno
Laura Leay

Andrew Cooper
Dave Adams
James Jones
Tom Hasell

John Jansen
Gabriele Clarizia
Paola Bernardo
Fabio Bazzarelli
Elena Tocci
Alberto Figoli

Neil McKeown
Kadhum Msayib
Mariolino Carta
Grazia Bezzu

EPSRC
Pioneering research and skills

COOPERATION

Double Nano Mem