Sorption Storage Technology Summary

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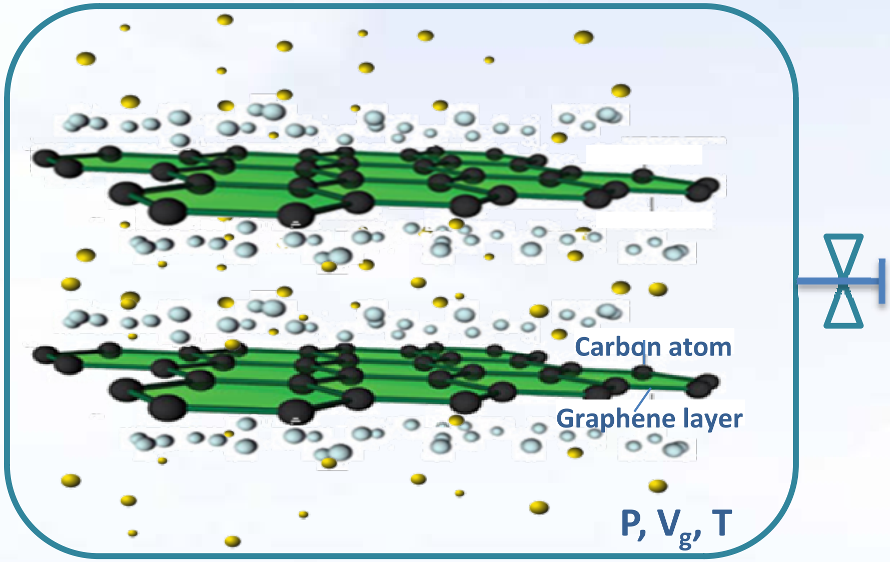
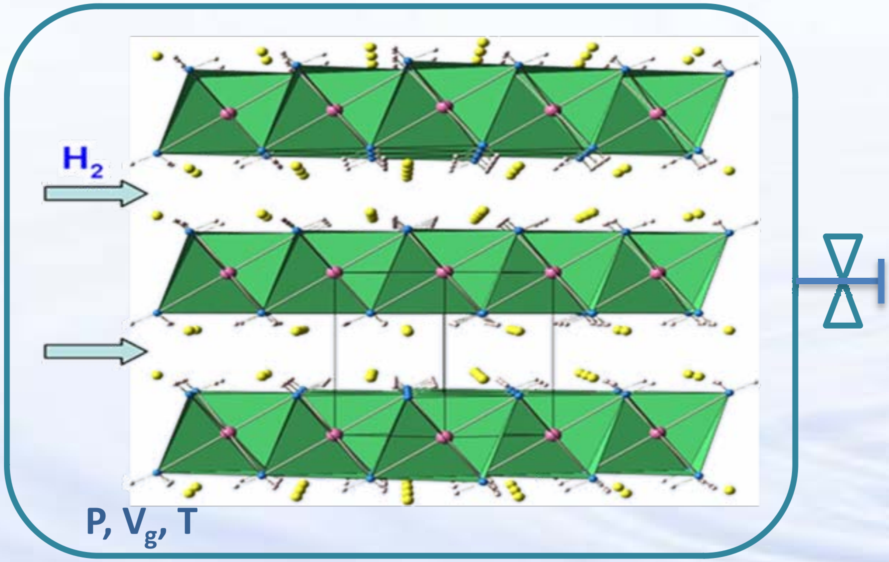
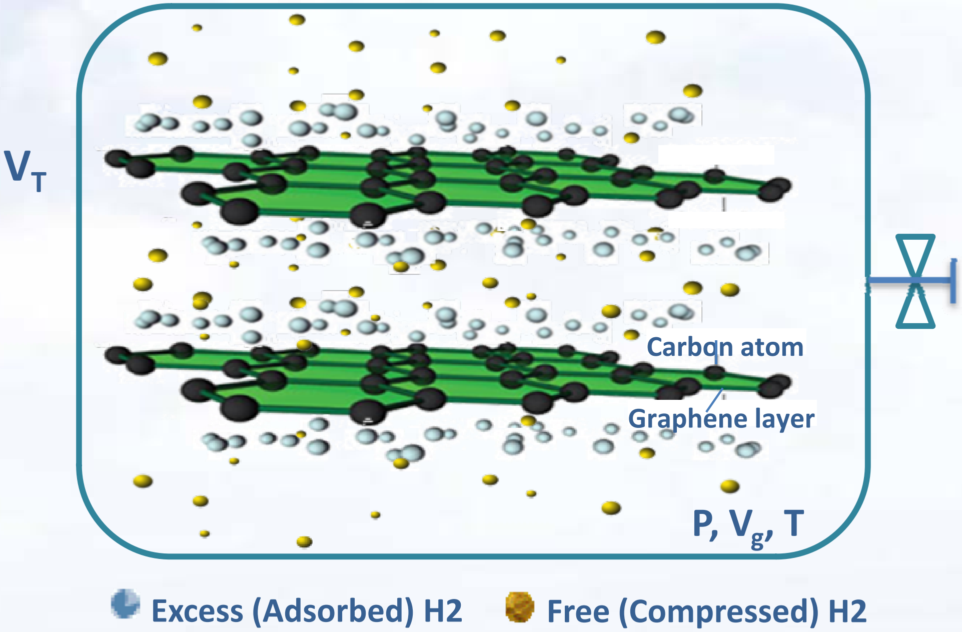


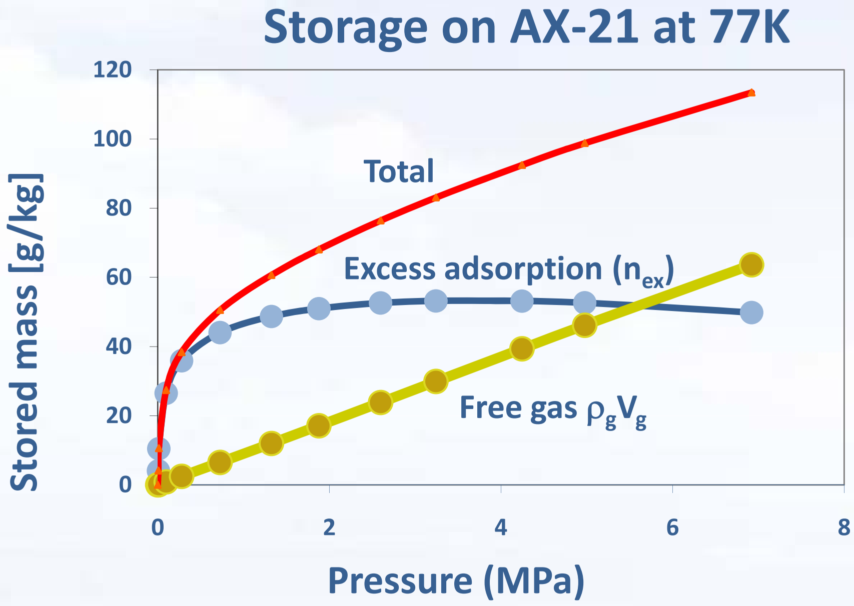


Compressed & Cryo-Compressed Hydrogen Storage Workshop
February 14 – 15, 2011, Washington, DC

Physisorption in supercritical region is mainly a surface phenomenon and the gas is stored in 2-phases: Adsorbed and Free

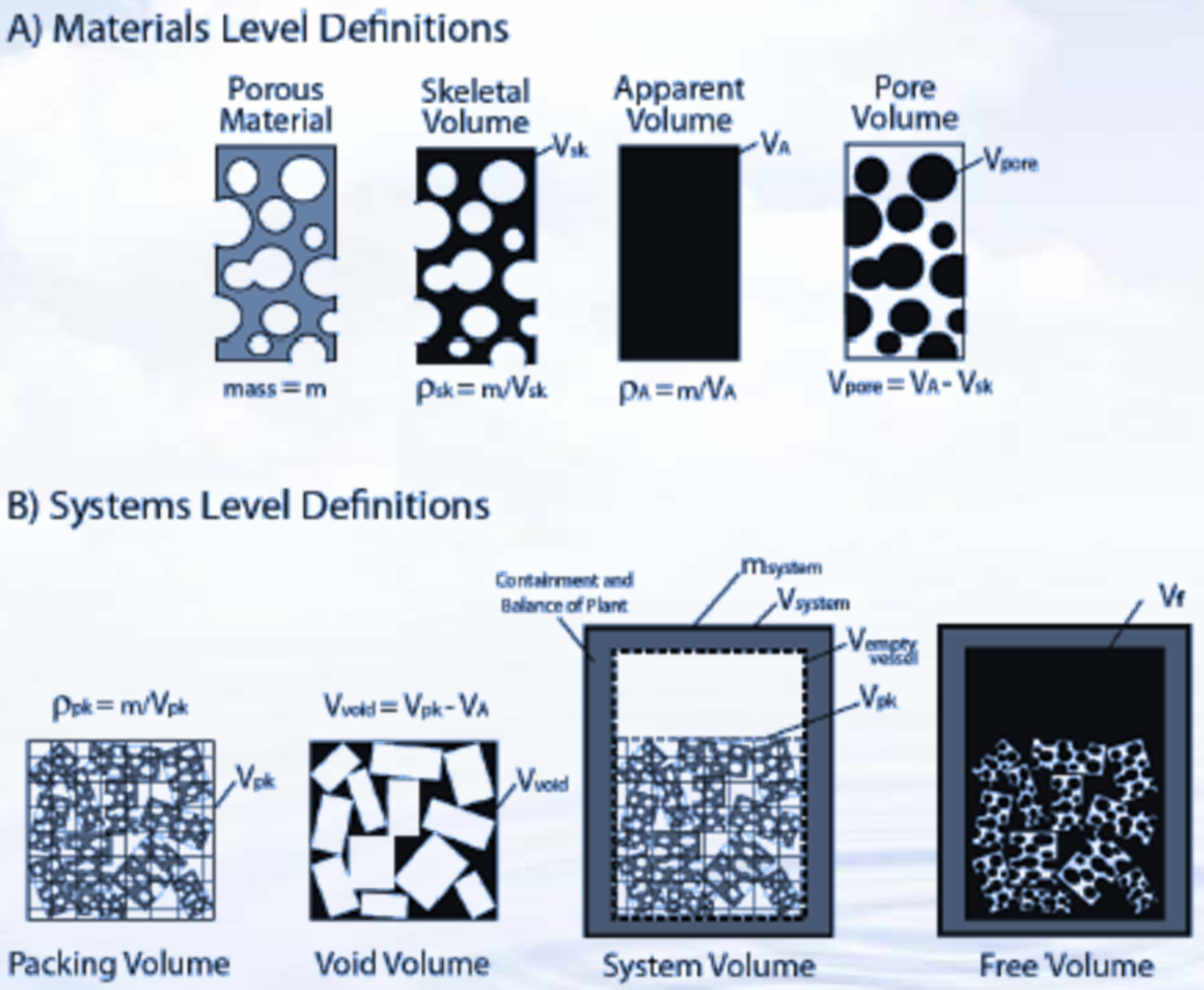
$V_{void} / V_{Total} = 90 – 50\%$




Storage on AX-21 at 77K

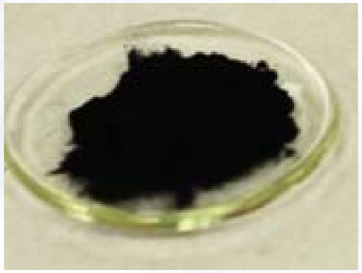
- Gas-solid interactions: mainly van der waals forces (not chemical binding)
- Average binding energy at practical coverage: 4 kJ/mol
- Adsorption is roughly proportional to the specific surface area (m^2/g) and/or micropore volume (ml/g) of the adsorbent
- Adsorption increases with: P, T^{-1}

Volume and Density Definitions

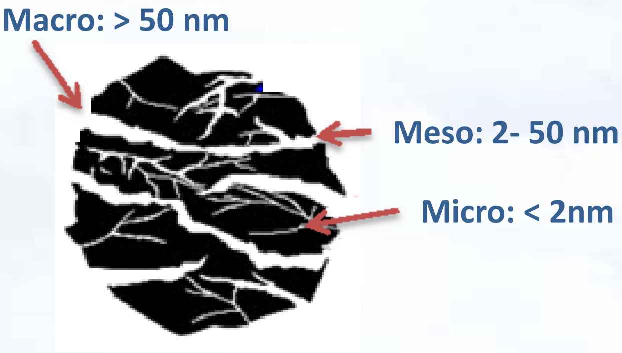


Gross, Karl J. et al; "Recommended Best Practices for the Characterization of Storage Properties of Hydrogen Storage Materials" DOE, 2010

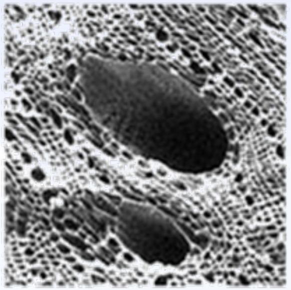
AX-21™ is representative of state of the art activated carbon*



Bulk powder



Porous structure



Porous structure

AX-21 Main Properties	
Bet Surface area (m^2/g):	2800
Micropore distribution (nm):	0.6 - 30
Pore volume (ml/g):	1.6
Skeleton density (g/ml):	2.2
Tap density (g/ml):	0.27

AX-21 Volume Usage	L/kg	%
Total (V_T) :	3.70	100
Skeleton:	0.45	12
Total Void (V_g) :	3.25	88
Pore:	1.6	43
Other:	1.65	45

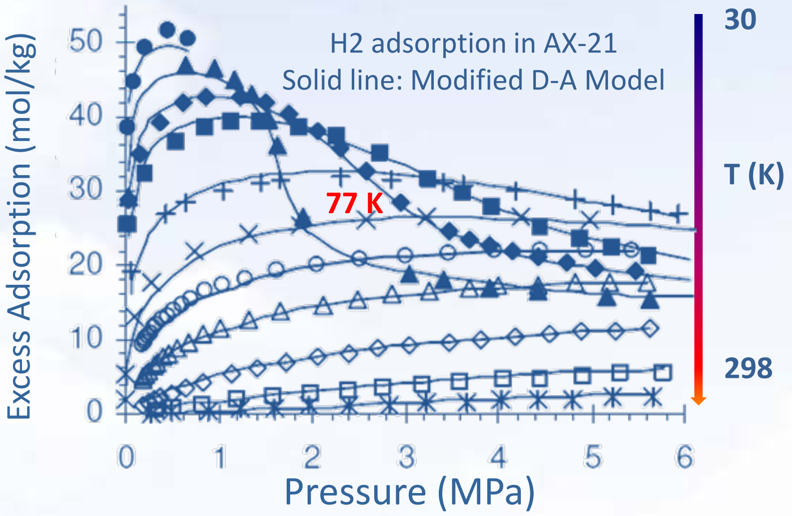
** Commercially available as Maxsorb: Kansai, Japan*

The adsorbent isotherms well fit our modified 5 parameters D-A model

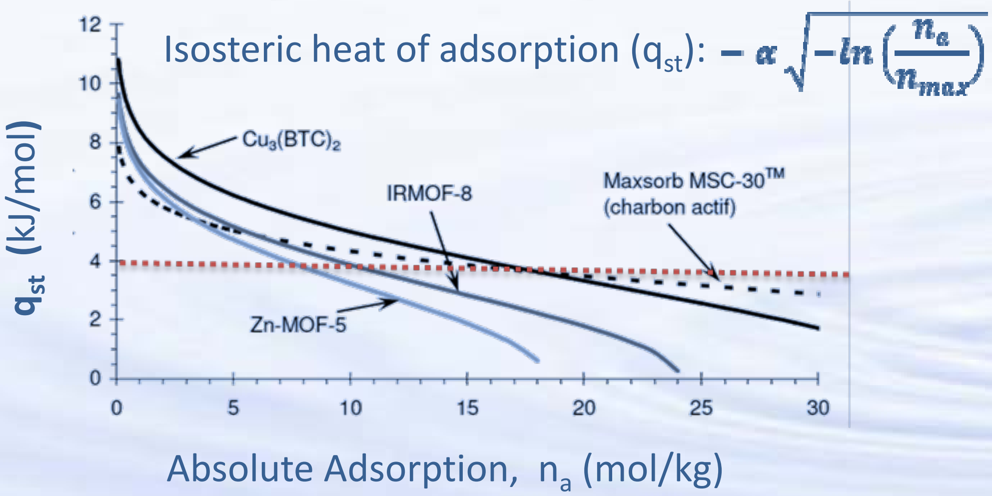
Modified Dubinin- Astakkov model

$$n_{ex} = n_{\max} \exp\left[-\left[\frac{RT}{\alpha+\beta T}\right]^2 \ln^2\left(\frac{P_0}{P}\right)\right] - \rho_g V_a$$

ε=α+βT (enthalpic and entropic contributions)



Analytical expressions of the thermodynamic properties of the adsorbed phase (U, S, q_{st})



Isosteric heat of adsorption (q_{st}): $-\alpha\sqrt{-\ln\left(\frac{n_a}{n_{max}}\right)}$

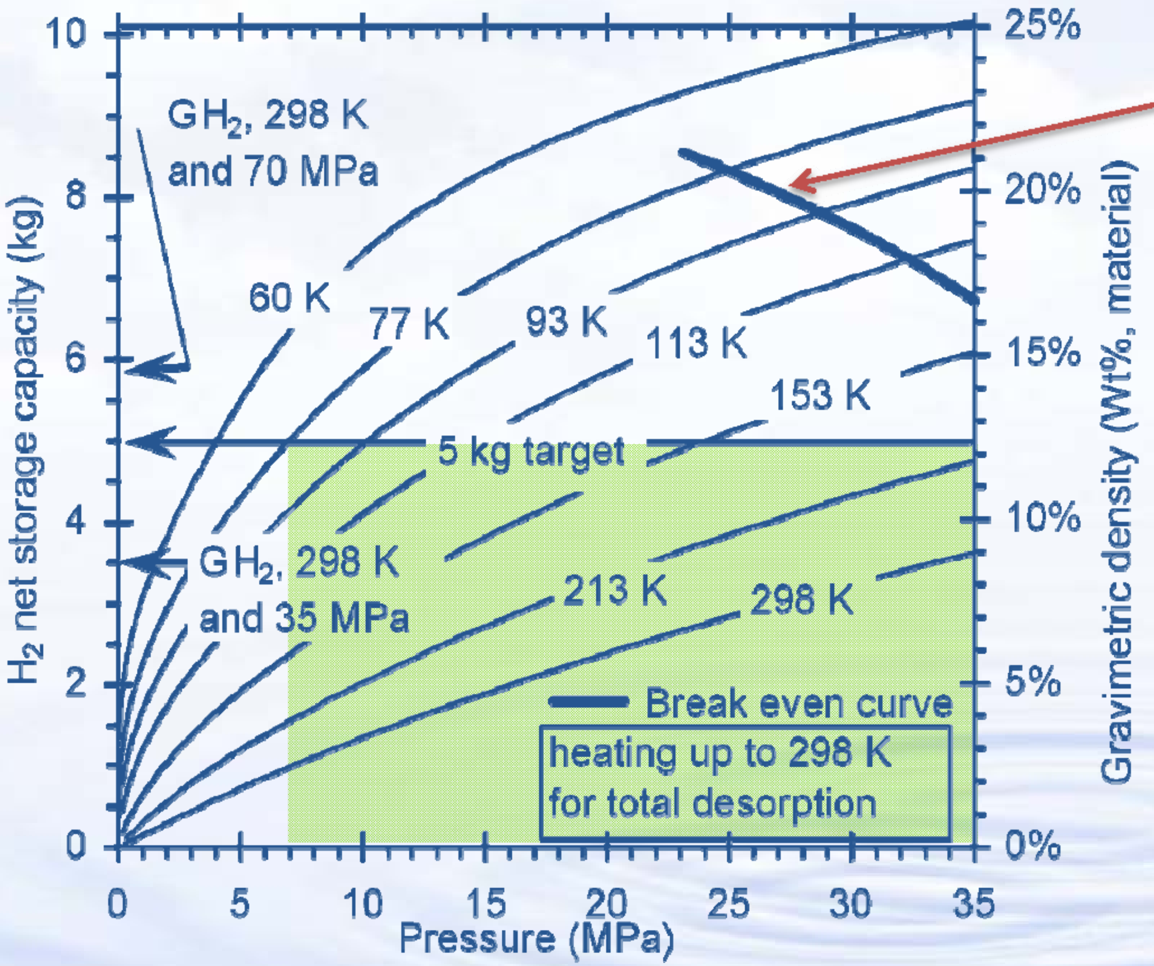
H_2 / AX-21™	
n_{max}	71.6 mol/kg (14 wt%)
P_0	1500 MPa
α	3.08 kJ/mol
β	0.0189 kJ/mol*K
V_a	1.4 ml/g
P_{max} (n_{max}/V_a)	51 mol/L

Adsorption (2009)

The charging {P,T} domain extends from as low as {70 bar, 80 K} to {350 bar, 213 K}

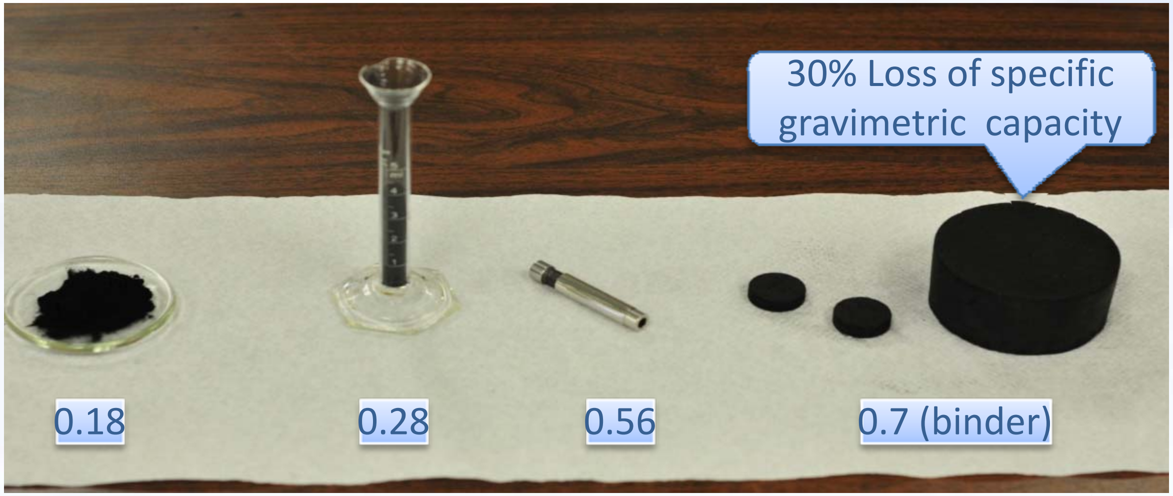
Net Storage Capacity of AX-21

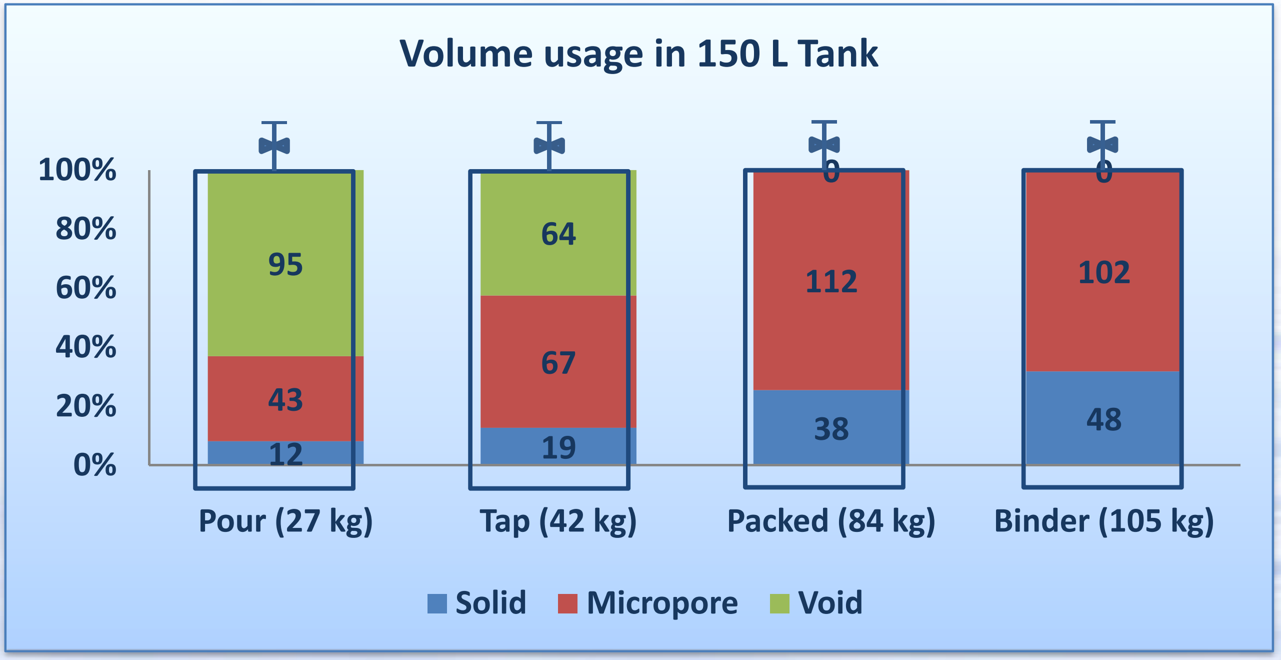
2.5 bar discharge pressure at 298 K
150 liter net storage volume



Break-even line with H_2 compression at the same P,T conditions

The adsorbent's volumetric capacity could be enhanced through proper packing and thus potentially reach the targets

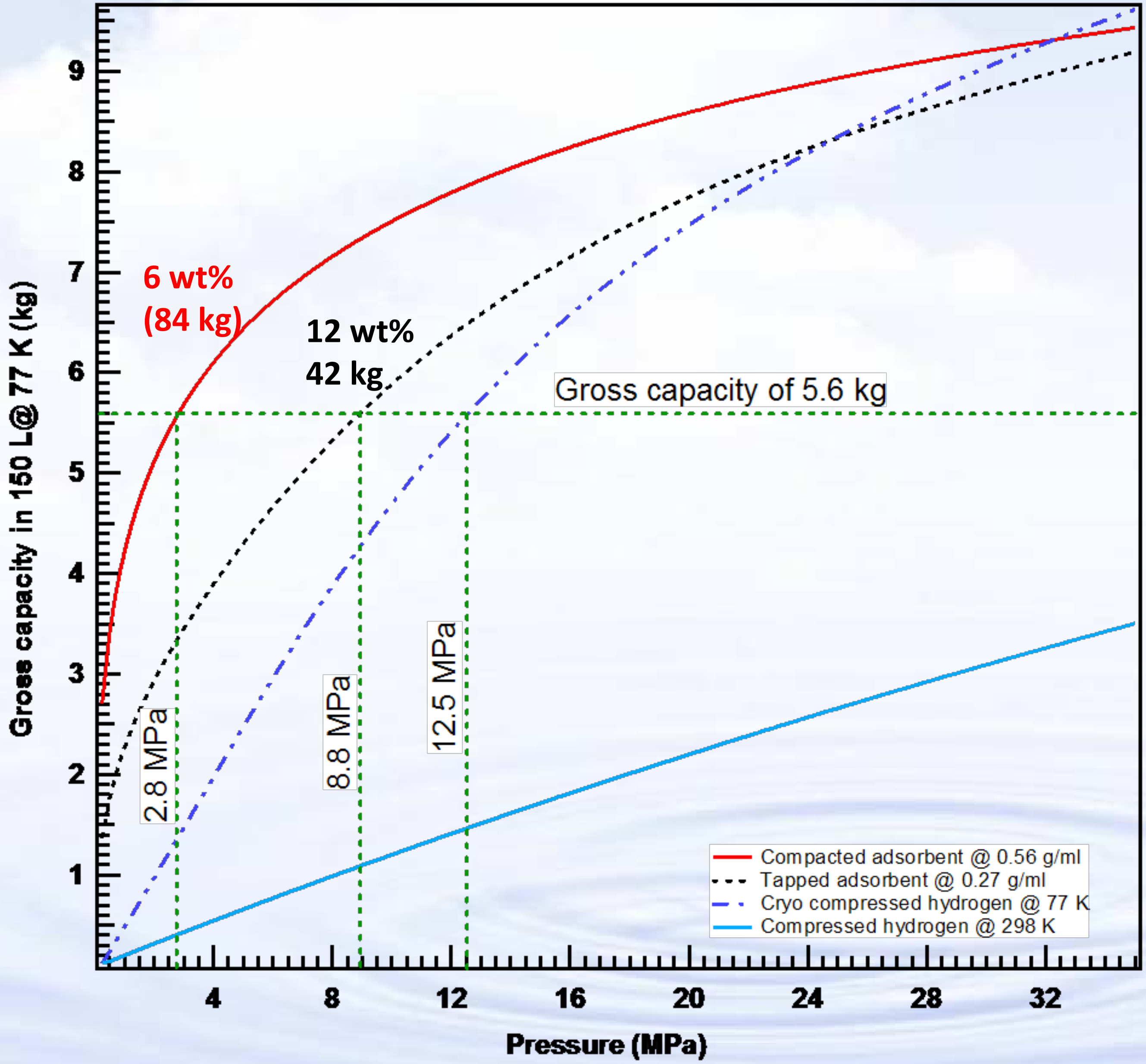




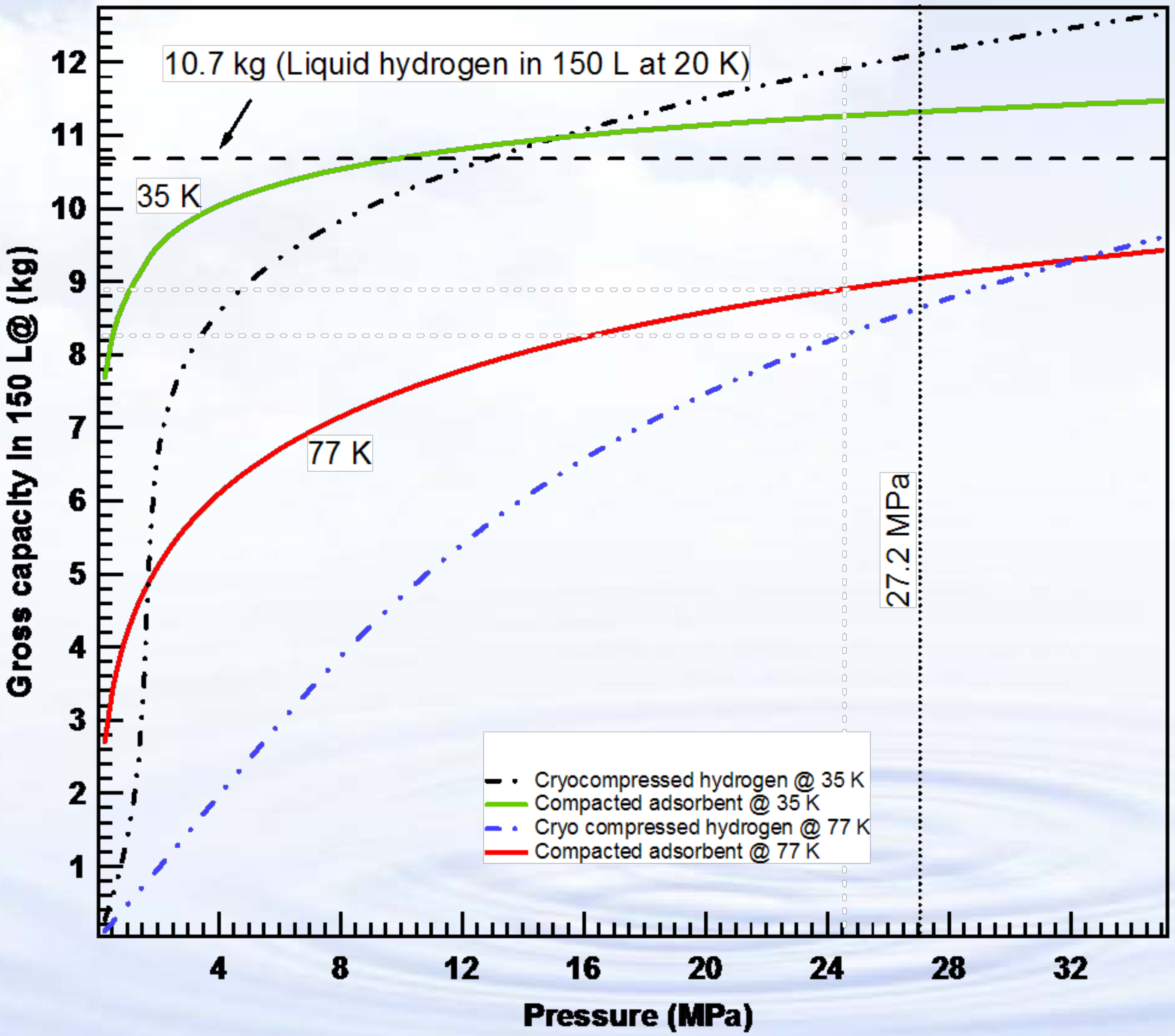
No Loss of surface area and/or micropore volume

Maxsorb	Density	SA BET	Micr. Vol. DR	Mesop. Vol. BJH	Tot. pore vol. At P/Po = 0.9
	(g/cm^3)	(m^2/g)	(ml/g)	(ml/g)	**(ml/g)**
Pour density	0.18	2800	0.99	0.63	**1.58**
Tap density	0.26	2798	1.00	0.57	**1.52**
Sample holder	0.28	2807	1.00	0.61	**1.54**
Sample holder (500 bar)	**0.56**	**2739**	**0.95**	**0.58**	**1.54**

This allows lower operating pressure, and therefore trade-off between shell and adsorbent weights and costs.



This advantage is maintained down to T near CP and may allow easier filling and prolonged dormancy



Conclusions

- In sorption systems the gas is stored in two phases: Adsorbed and Free. The void fraction varies from 90 to 50%.
- Many similarities with compressed H2 storage, however advantage is limited to low T.
- Enables low operating pressure (specially the optimized materials), and increased dormancy.
- Tradeoffs: more thermal management, less energy efficient, increased weight.