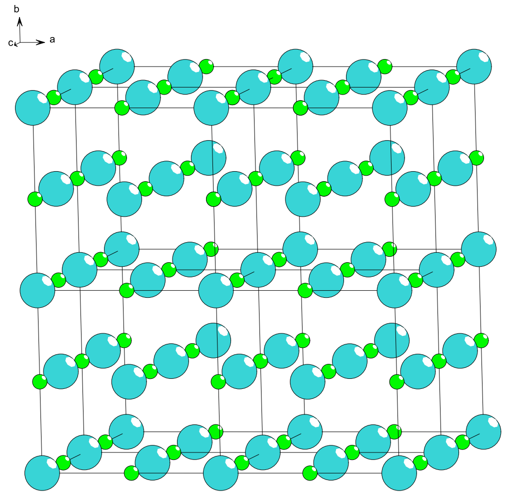
Hydrogen storage
Making the hydrogen economy a reality

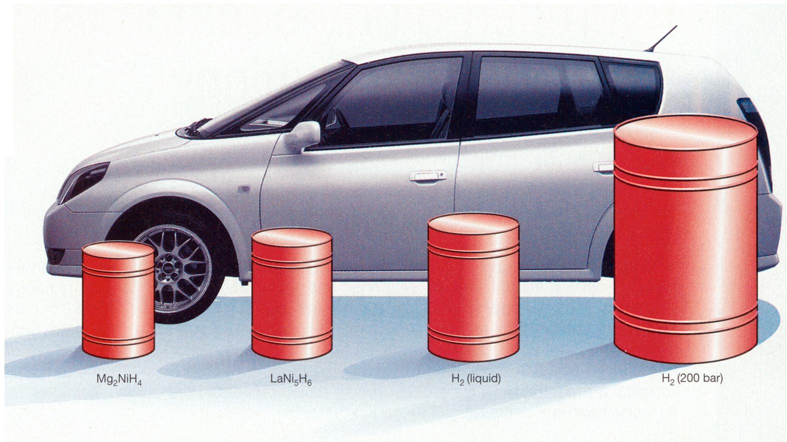
Sabrina Sartori
Physics Department, Institute for Energy Technology,
Kjeller, Norway

sabrinas@ife.no
www.ife.no

Overview

- Why hydrogen storage?
- Materials for hydrogen storage
- "Looking" at the atoms





We live in exciting times

- Regular progress toward a hydrogen economy
- Worthy challenges remain to be attacked, and solved
- Interest in hydrogen economy research from industry, academia, and governments around the world
- Economic and social benefits to those who find the answers

The hydrogen economy - a flow of energy

- Conversion of primary energy to a clean carrier, hydrogen
- Storage
- Transportation and delivery of hydrogen to the consumer
- Conversion to useful work

What the hydrogen economy does for society

- New industries will produce materials
- Changes in vehicle power sources
- Reduced pollution

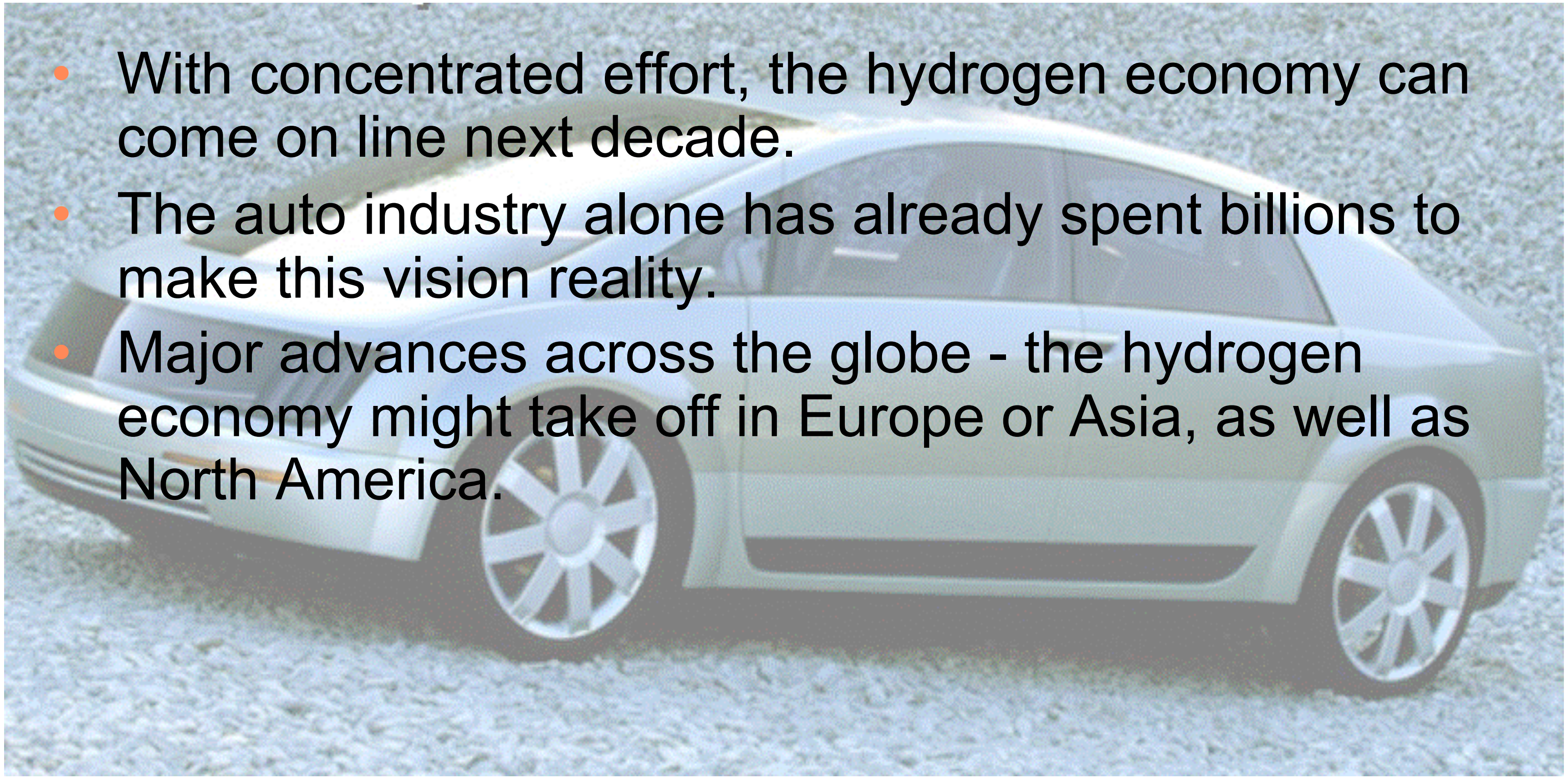
Many significant accomplishments...

- Doubling of solid phase hydrogen storage capacity
- Expanding options to make, store and use hydrogen
- Vehicle material content becomes ever more sophisticated

...but challenges remain

- Reduce cost, and improved function of storage.
- Establish a production and delivery infrastructure nationwide/worldwide.
- Establish the industry on a scale to serve the energy and transportation industries.

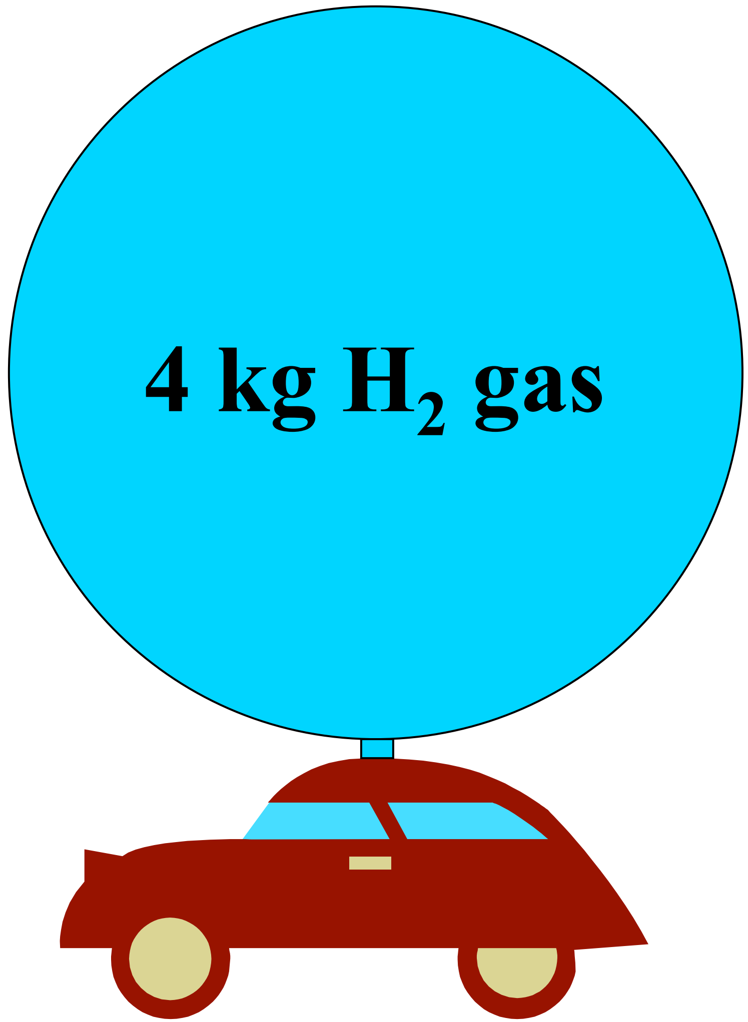
When and where



- With concentrated effort, the hydrogen economy can come on line next decade.
- The auto industry alone has already spent billions to make this vision reality.
- Major advances across the globe - the hydrogen economy might take off in Europe or Asia, as well as North America.

Hydrogen

At ambient temperature and atmospheric pressure, 1kg of gas hydrogen has a volume of 11 m^3



for the car of the future…

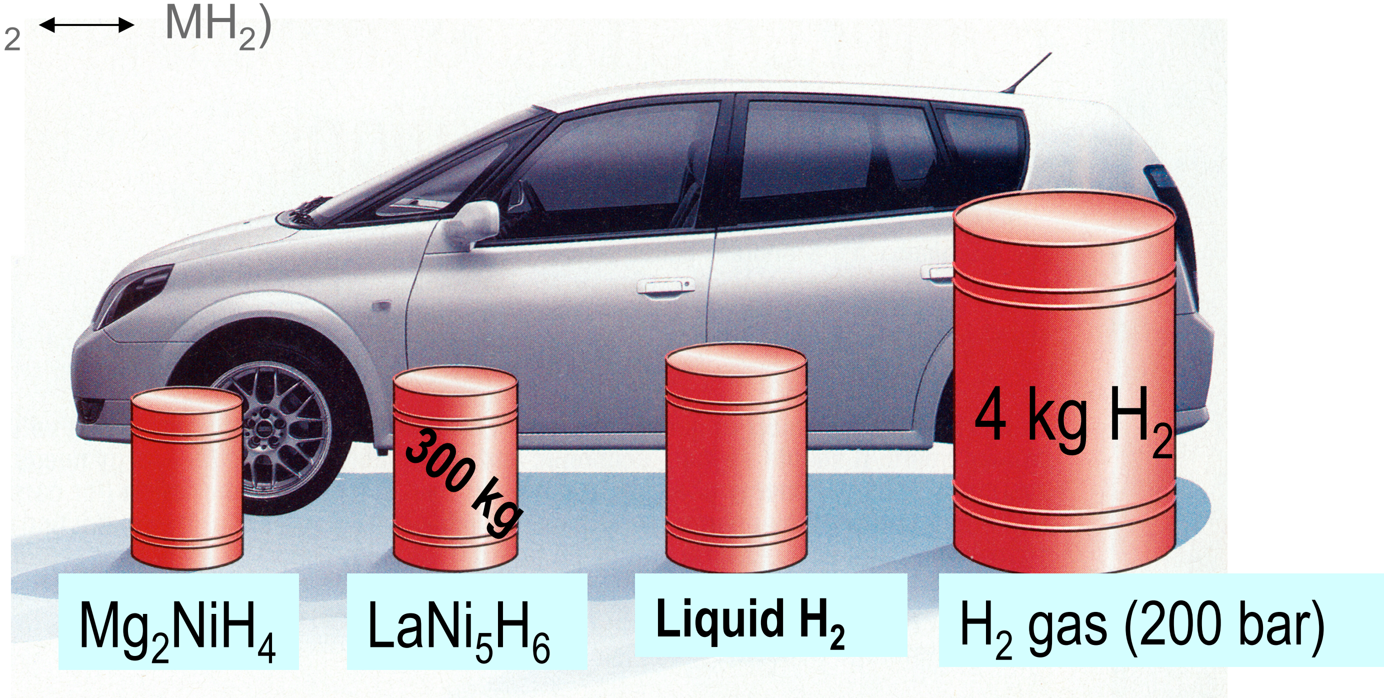
... we need to store it efficiently!!!

Hydrogen

Storage:

- Compressed gas
- liquid hydrogen (21 K = - 252 °C)
- storage in solid materials

(f.ex. $M + H_2 \longleftrightarrow MH_2$)



The Challenge: Goals for hydrogen storage

- **2010: ≥ 6 wt%**
- **2015: ≥ 9 wt%**

Storage Parameter	2010 Target
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)	2 kWh/kg (0.06 kg H_2/kg system or 6 wt.%)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	1.5 kWh/L (0.045 kg H_2/L system)
Durability/Operability	
• Operating ambient temperature	–30/50 °C (sun)
• Min/max delivery temperature	–40/85 °C
• Cycle life (1/4 tank to full)	1000 Cycles
• Min delivery pressure from tank; FC=fuel cell, ICE=internal combustion engine	4 FC/35 ICE Atm (abs)
Charging/Discharging Rates	
• System fill time (for 5 kg H_2)	3 min
• Min full flow rate	0.02 (g/s)/kW
• Transient response 10%–90% and 90%–0%	0.75 s

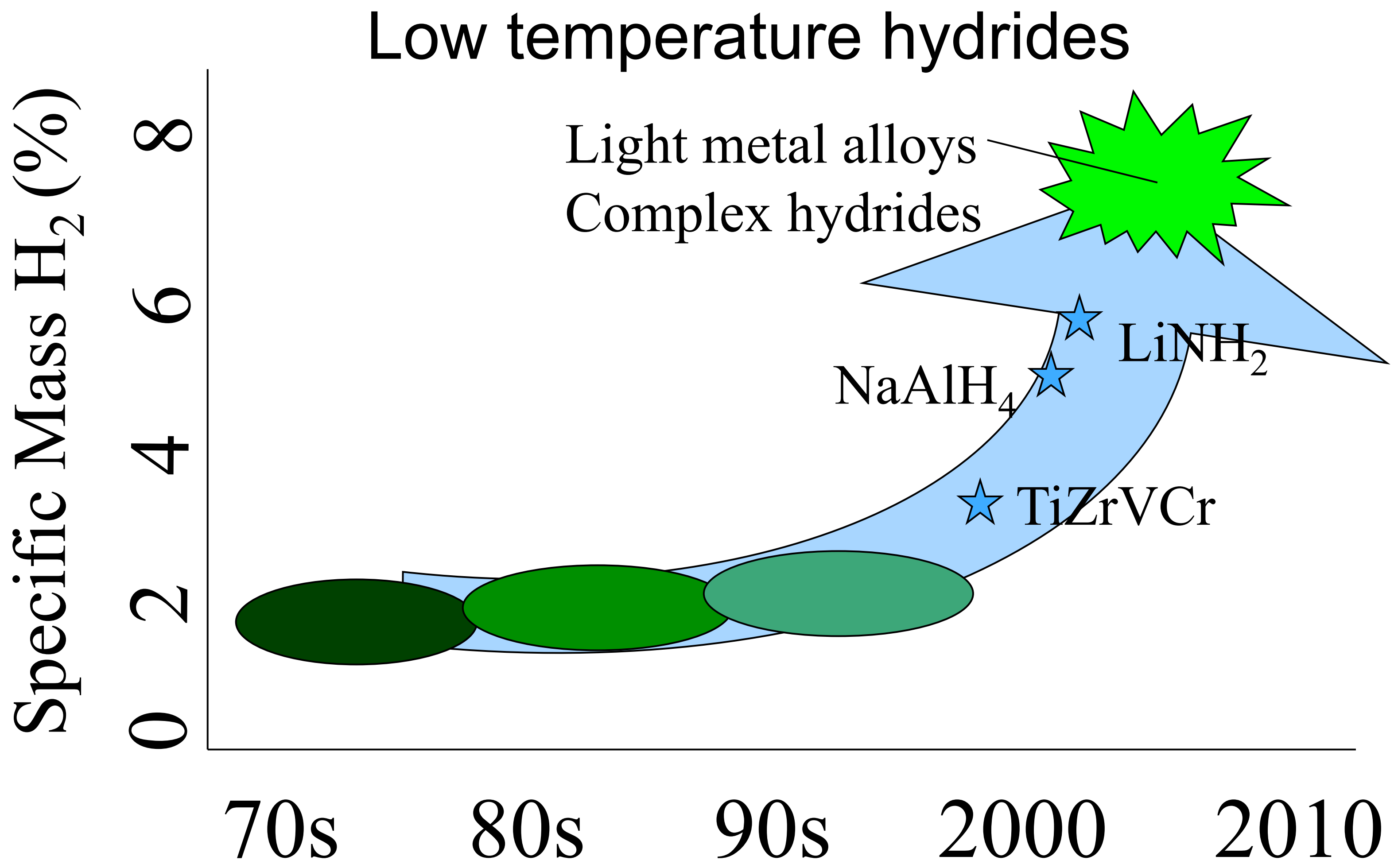
Hydrogen storage in solid materials

What we need:

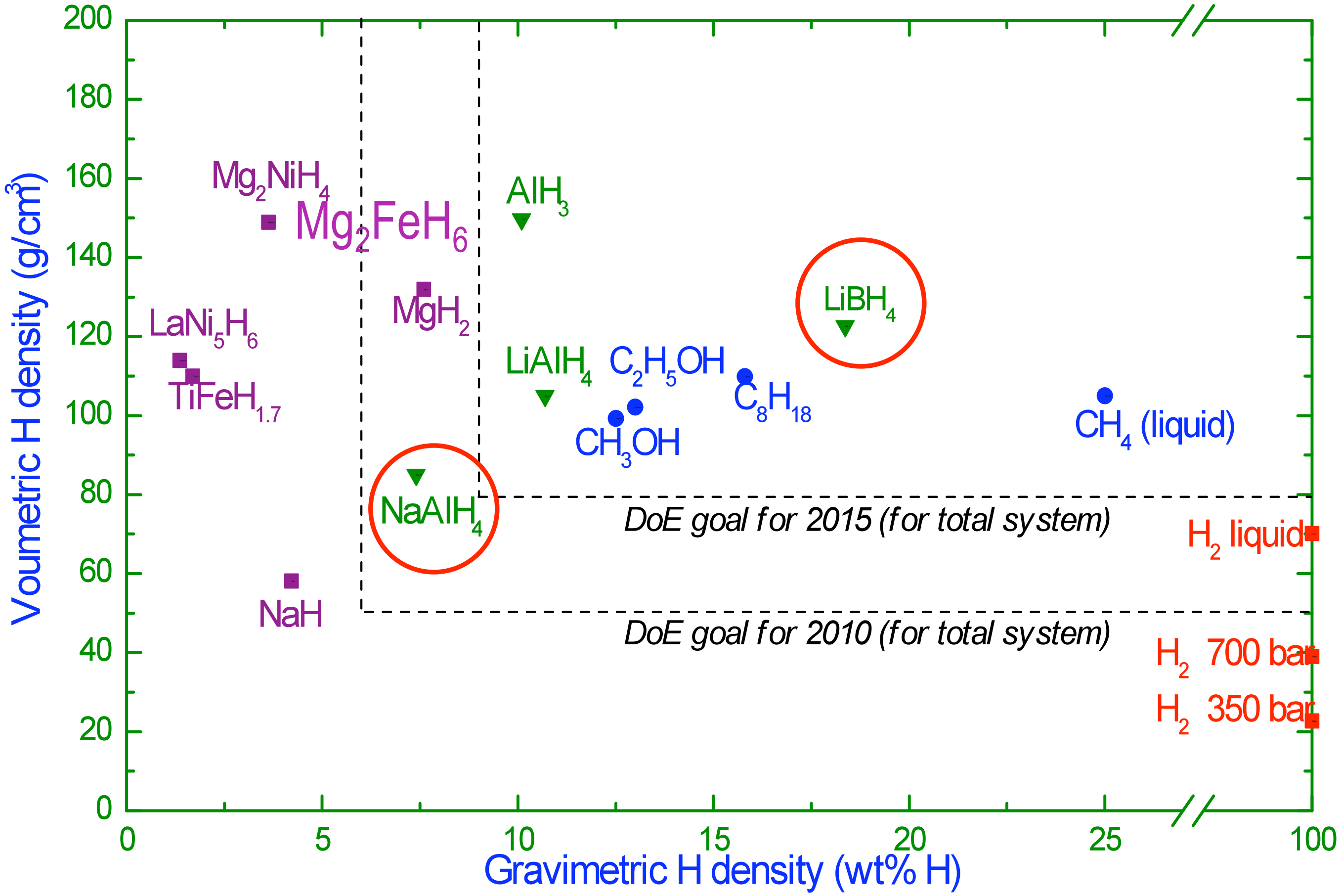
- high quantity of hydrogen stored *(gravimetric and volumetric)*
- Consumers want a vehicle that refills rapidly, hydrogen should go <u>in</u> and <u>out</u> quickly and at moderate pressure and temperature
- the material should be cheap
- and resist after several cycle

Storage method	ρ_m [mass%]	ρ_V [kg H_2 m^{-3}]	T [°C]	p [bar]	Phenomena and remarks
High pressure gas cylinders	13	<40	RT	800	Compressed gas (molecular H_2) in light weight composite cylinders (tensile strength of the material is 2000 MPa)
Liquid hydrogen in cryogenic tanks	size dependent	70.8	-252	1	Liquid hydrogen (molecular H_2), continuous loss of a few % per day of hydrogen at RT
Adsorbed hydrogen	≈ 2	20	-80	100	Physisorption (molecular H_2) on materials e.g. carbon with a very large specific surface area, fully reversible
Absorbed on interstitial sites in a host metal	≈ 2	150	RT	1	Hydrogen (atomic H) intercalation in host metals, metallic hydrides working at RT are fully reversible
Complex compounds	<18	150	>100	1	Complex compounds ($[AlH_4]^-$ or $[BH_4]^-$), desorption at elevated temperature, adsorption at high pressures
Metals and complexes together with water	<40	>150	RT	1	Chemical oxidation of metals with water and liberation of hydrogen, not directly reversible?

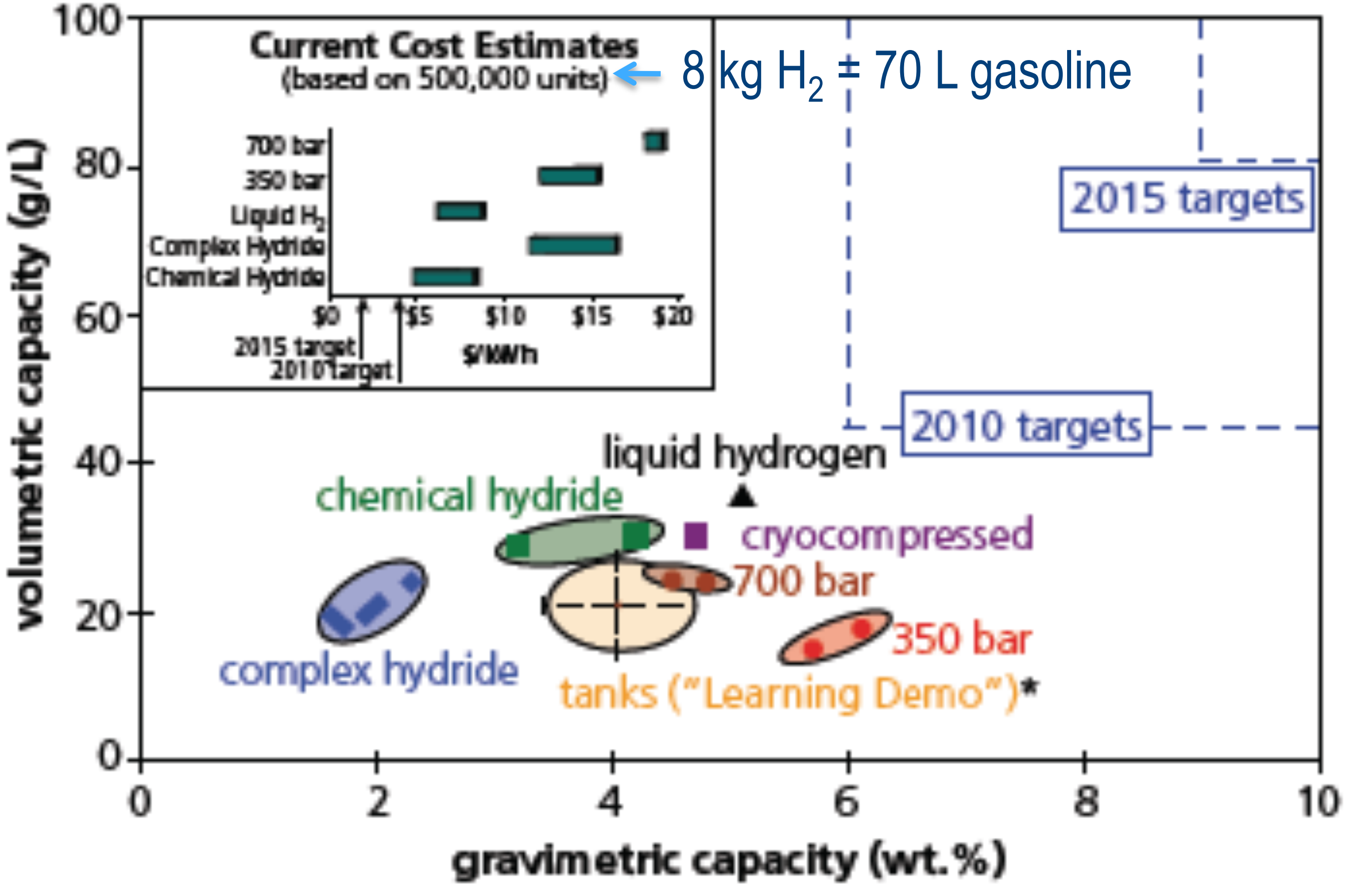
New materials spur rapid progress



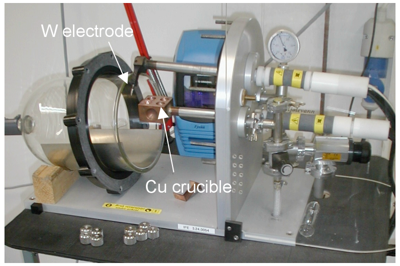
Solid Materials and targets

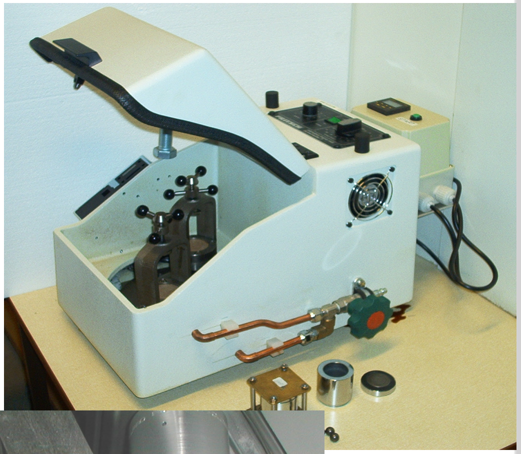


Hydrogen storage systems



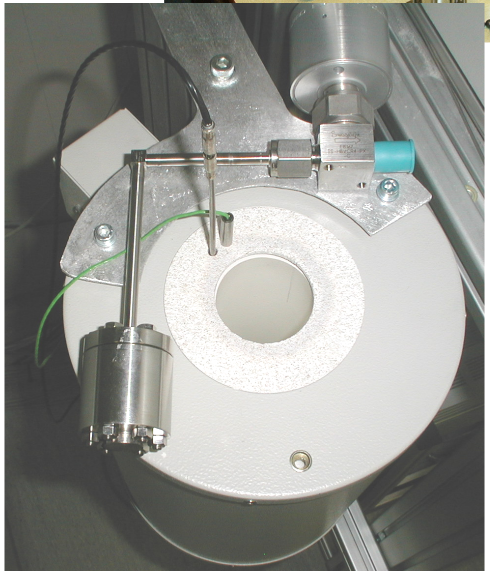
Hydrogen storage in solid materials





activities:

- Synthesis of new materials
- understanding the structure
- measuring the stability
- measuring the kinetics
- study of the reaction



$2KH + NaAlH_4 \rightarrow K_2NaAlH_6$

Hydrogen storage in solid materials

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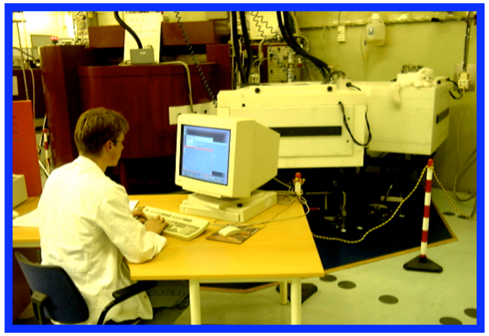
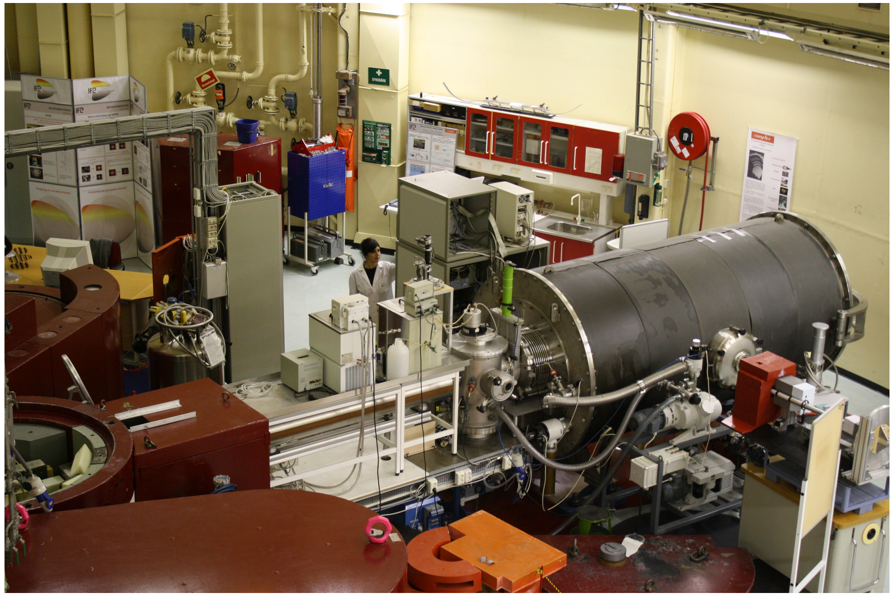


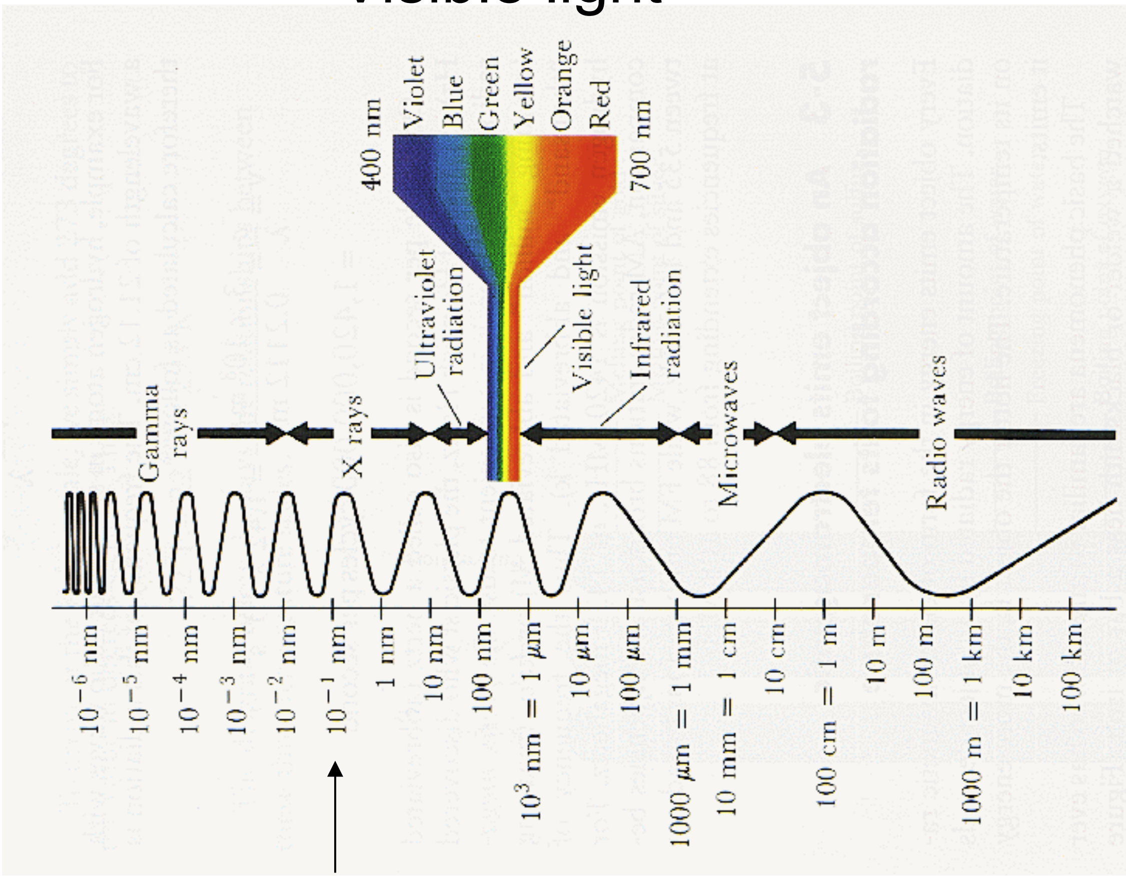
JEEP-II



Small-angle neutron scattering (SANS)

Structure of materials

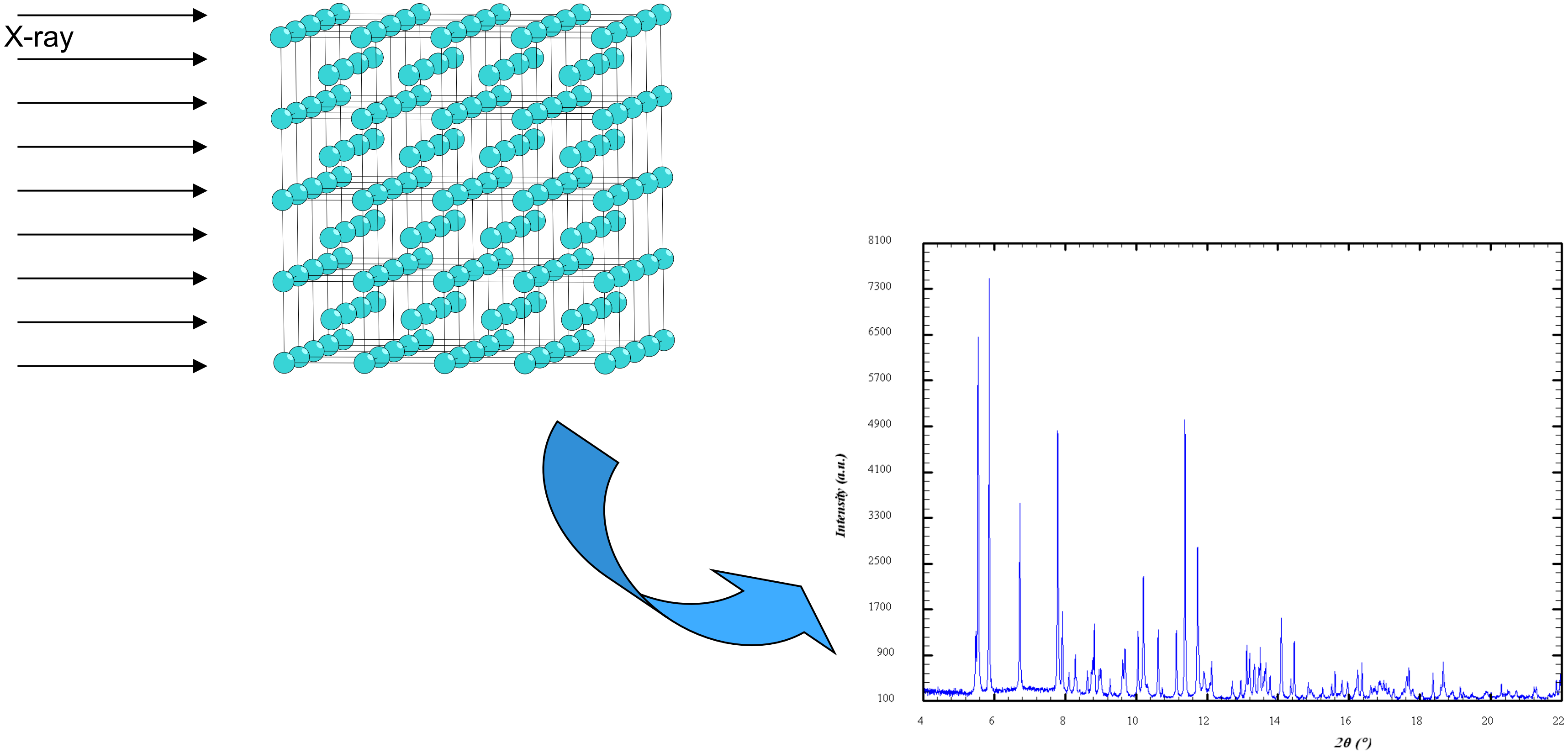
Visible light



We want to ”see” at this level (0.1 nm = 1 Å = ca. distance between atoms)

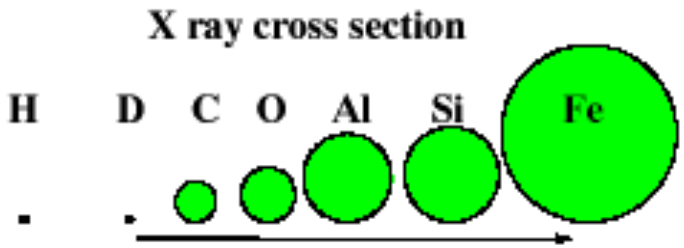
Using X-ray to ”see”

diffraction



Using X-ray to ”see”

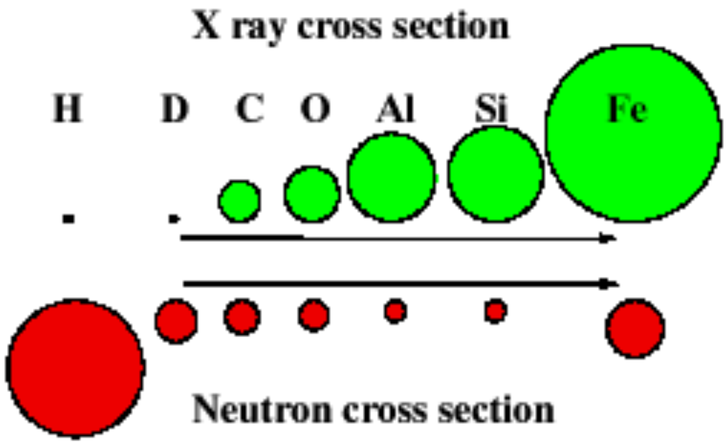
... doesn’t work always so good!



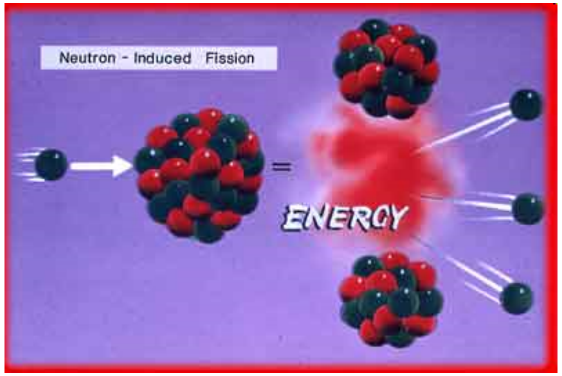
Heavy atoms scatters more X-ray

Using X-ray to ”see”

... doesn’t work always so good!

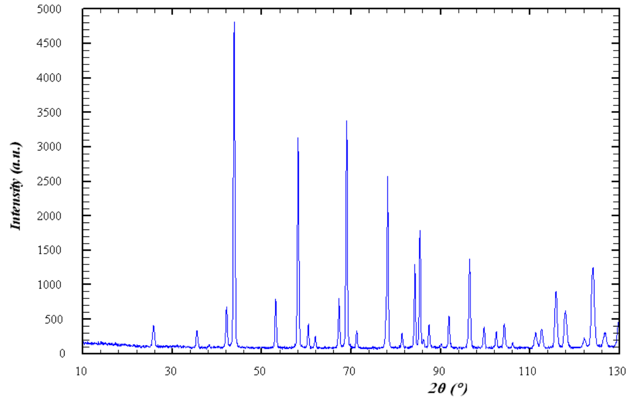


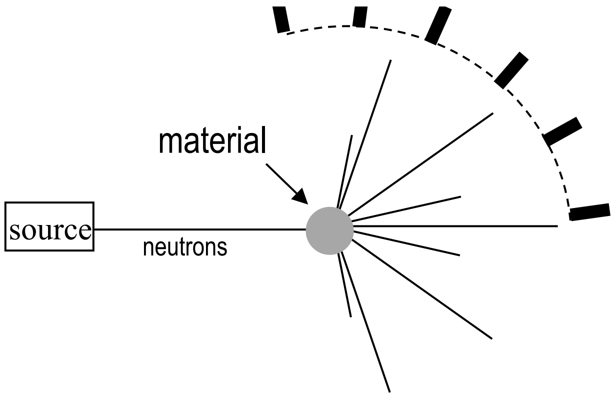
This is different with neutrons!



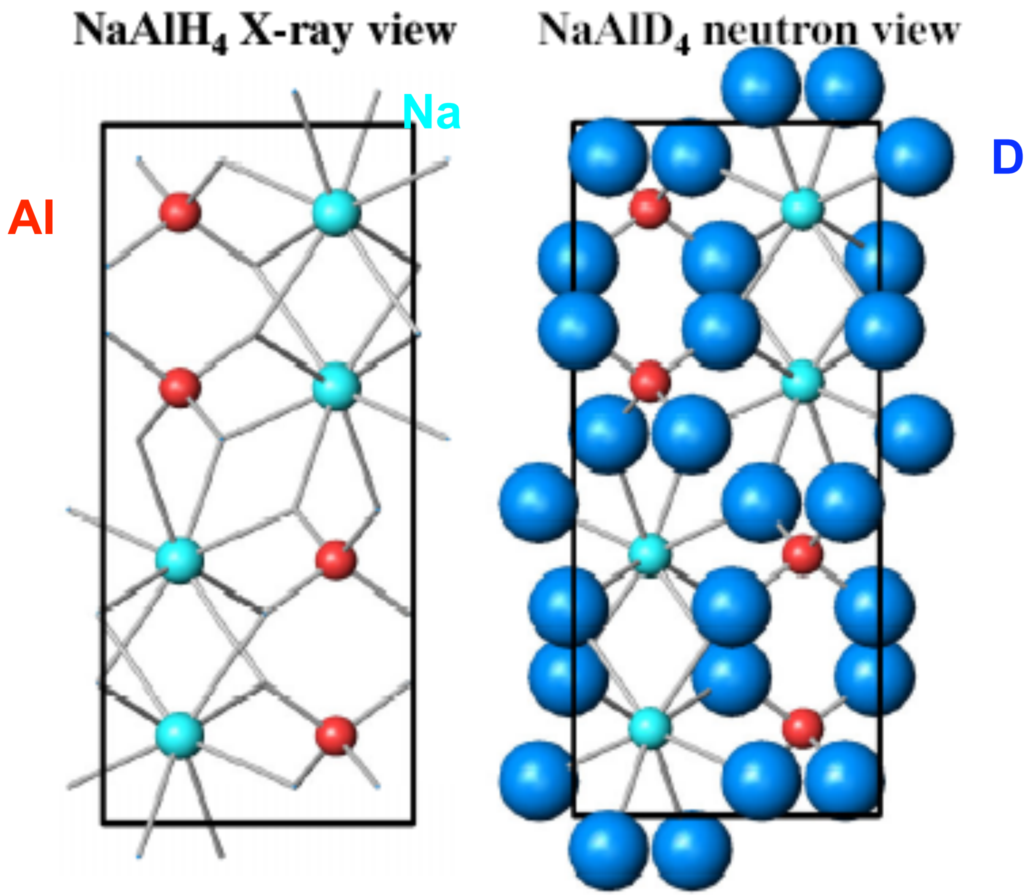
Using neutrons to ”see” hydrogen

We can use neutrons in the same way as X-ray



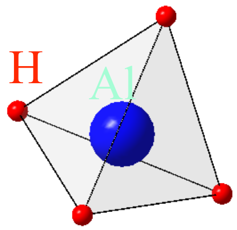


Using neutrons to ”see” hydrogen

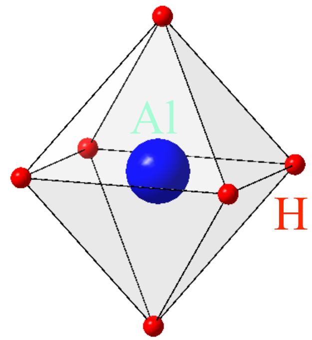


Examples: Alanates

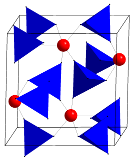
$NaAlH_4$
Na_3AlH_6
$LiAlH_4$
β-$LiAlH_4$
Li_3AlH_6
$KAlH_4$
$Mg(AlH_4)_2$
Sr_2AlH_7
$BaAlH_5$
Ba_2AlH_7
Na_2LiAlH_6
K_2NaAlH_6
$LiMg(AlH_4)_2$
$LiMgAlH_6$
$Ca(AlD_4)_2$
$CaAlD_5$



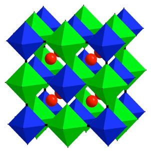
AlH_4^-



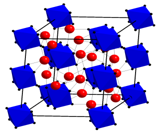
AlH_6^{3-}



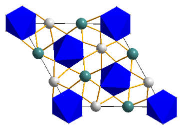
$LiAlH_4$



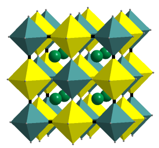
Na_2LiAlH_6



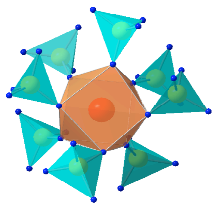
Li_3AlH_6



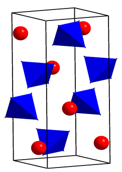
$LiMgAlH_6$



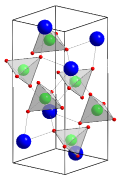
K_2NaAlH_6



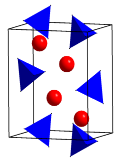
$Ca(AlH_4)_2$



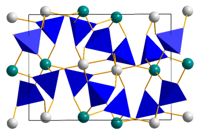
$NaAlH_4$



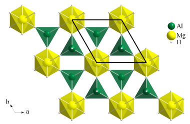
β-$LiAlH_4$



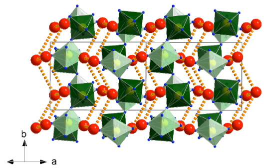
$KAlH_4$



$LiMg(AlH_4)_3$



$Mg(AlH_4)_2$

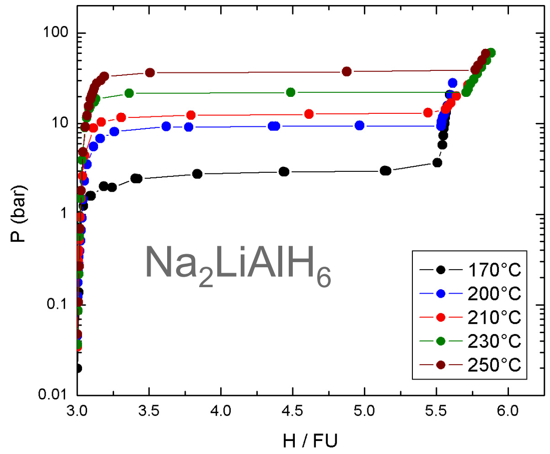


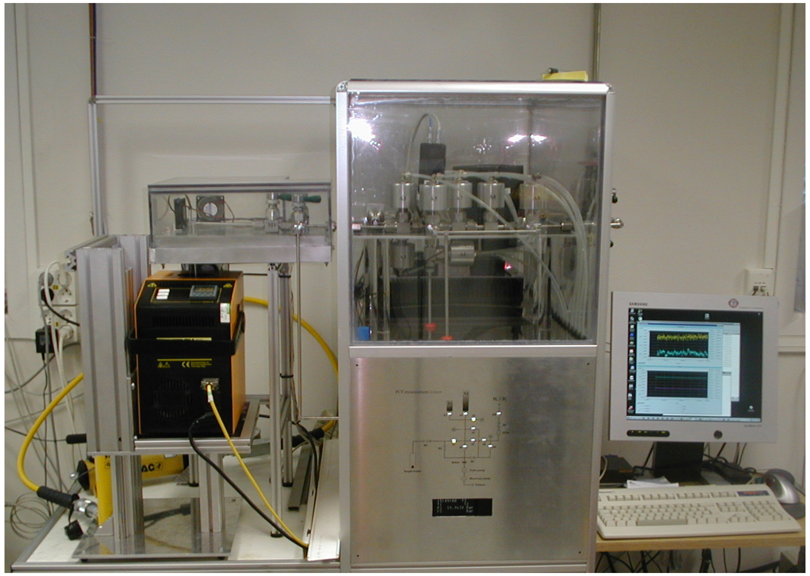
$CaAlH_5$

Hydrogen storage in solid materials

Our activities:

- Synthesis of new materials
- understanding the structure
- measuring the stability
- measuring the kinetics
- study of the reaction





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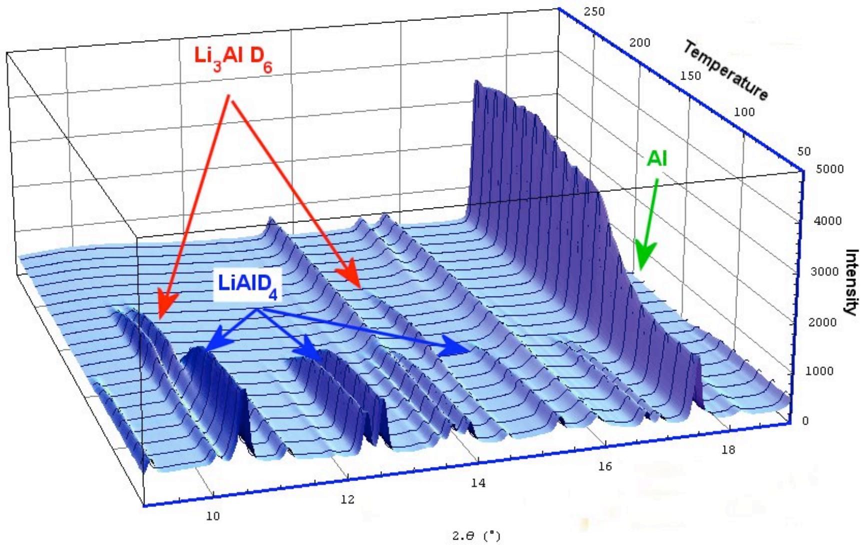
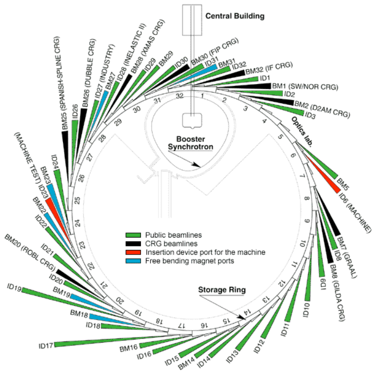
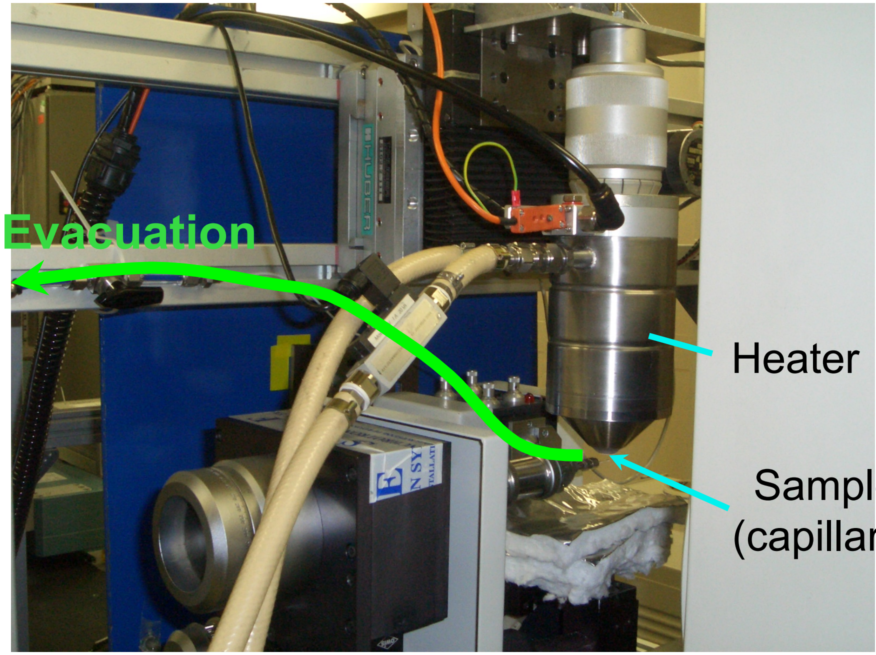
ESRF (Grenoble, Frankrike)



Synchrotron powder X-ray diffraction



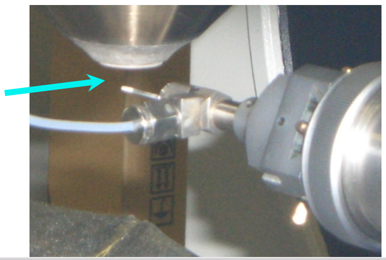
Swiss-Norwegian Beamline (BM01)



Heater

Sample (capillary)

- Heating under evacuation 1˚C/min.
- Diffraction data collected every 2min



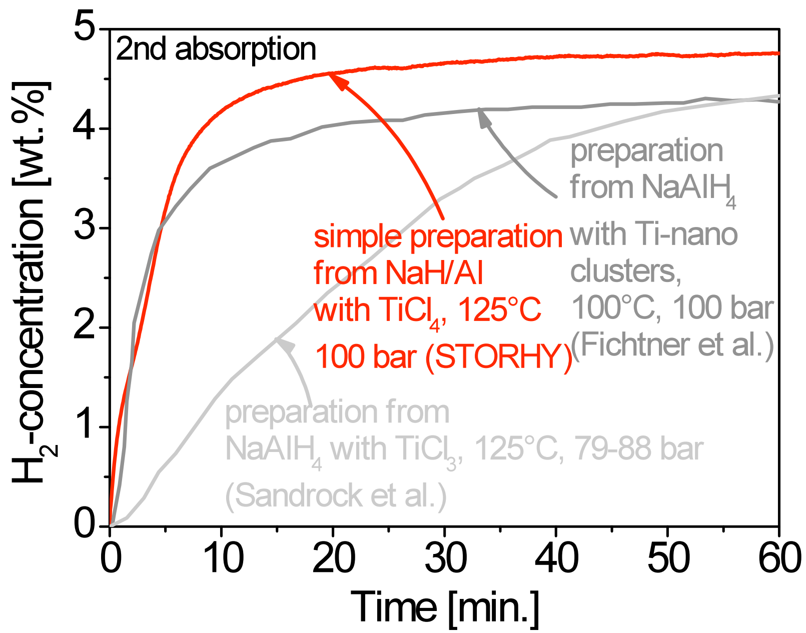
Dehydrogenation reaction studied by *in situ* SR-XRD

Upscaling of Solid Storage Tank

Concept for upscaling of material production processes

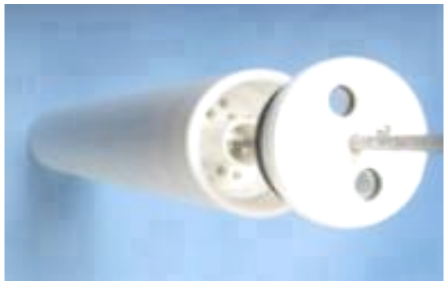
Evaluation of low cost (< 1 Euro/kg) production routes for complex hydrides using catalysed $NaAlH_4$ as model material

Up-scaling to kg amounts demonstrated



Design and development of operational prototype solid storage tanks

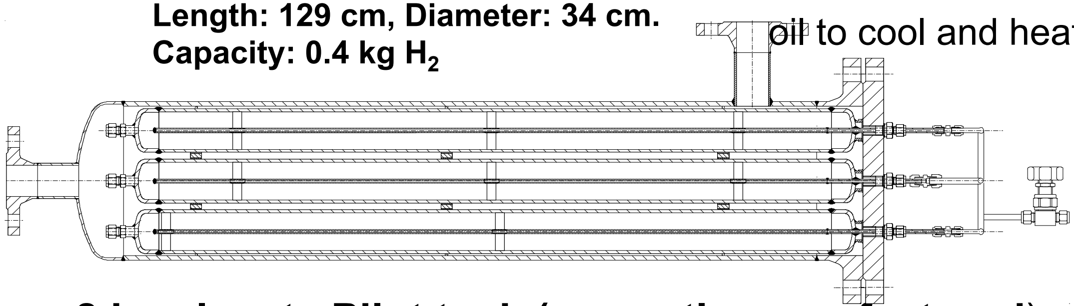
Laboratory tank for 0.5 kg of alanate



Length: 40 cm / Diameter: 6 cm Capacity: 20 g H_2

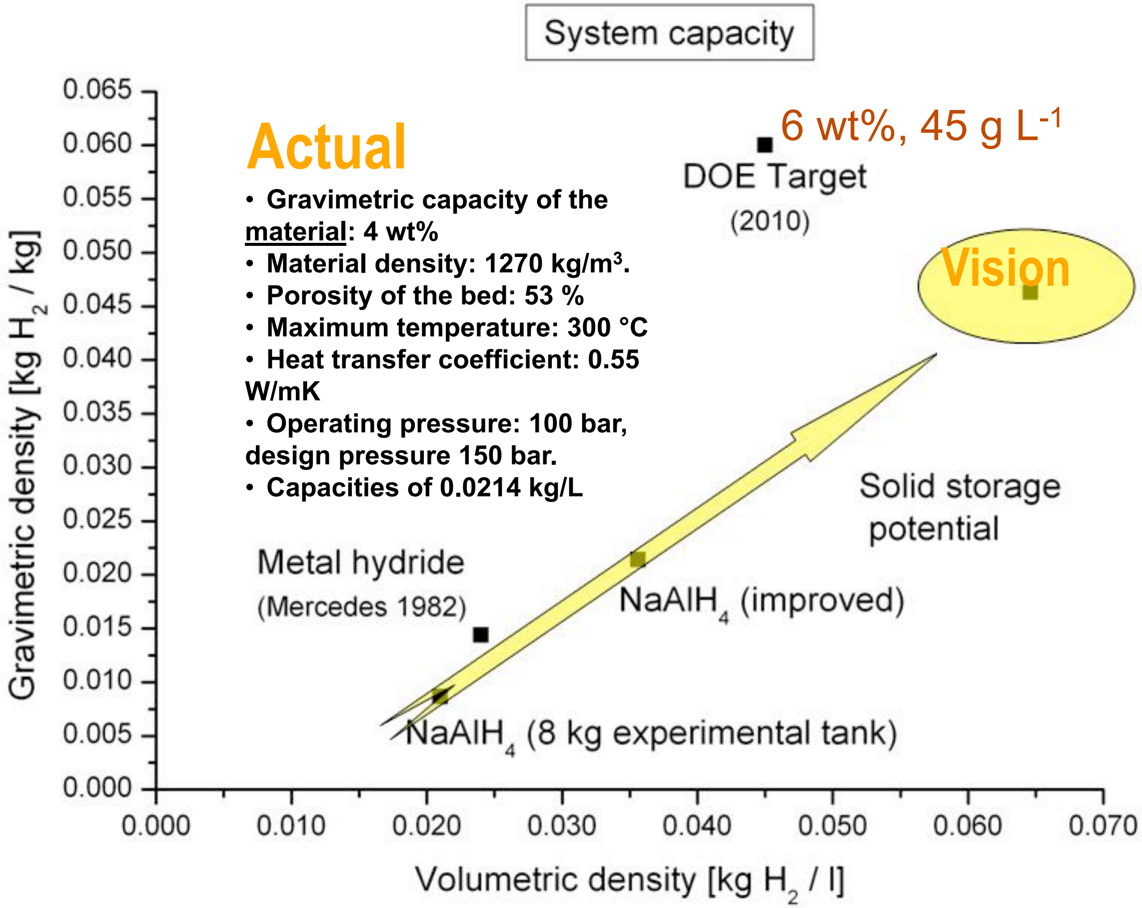
Length: 129 cm, Diameter: 34 cm. Capacity: 0.4 kg H_2

Cilinders surrounded by oil to cool and heat



8 kg alanate Pilot tank (currently manufactured)

Estimation for system capacities in different hydrogen storage systems



Actual

- Gravimetric capacity of the material: 4 wt%
- Material density: 1270 kg/m³.
- Porosity of the bed: 53 %
- Maximum temperature: 300 °C
- Heat transfer coefficient: 0.55 W/mK
- Operating pressure: 100 bar, design pressure 150 bar.
- Capacities of 0.0214 kg/L

Solid materials:

- **Good safety aspect;**
- **High volumetric density;**
- **EU projects on tanks NessHy/NanoHy/FlyHy**

Improved tank ?

- **Porosity of the bed: 20 % (compressing the powder)**
- **Improved heat coefficient transfer**
- **Maximum operating pressure: 50 bars**
- **Maximum temperature : 215 °C**
- **Capacities of 0.0356 kg/L**

Solid Storage summary

- At present, no solid storage material fulfils the major targets for automotive applications
- Further research for novel storage materials with improved storage densities, kinetics and thermodynamic behaviour as well as for advanced system components, e.g. heat exchanger, is still required
- tank development demonstrates feasibility of a fast heat removal using lightweight complex hydrides
- up-scaling results show high potential for mass production of complex light weight hydrides at low costs
- For technical applications is not acceptable that after low-pressure rehydrogenation, the system is not rehydrogenated as quickly as prior (system without cycle stability);
- High charging rates under low pressures are still a challenge on the way to a practicable solid-state hydrogen- storage material for fuel-cell-powered cars.

see www.hynor.no