Fuel Cell

Hydrogen, A fast growing niche in the Energy Market

SETARAM
Instrumentation

KEP Technologies

The Hydrogen Economy

"I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. I believe then that when the deposits of coal are exhausted, we shall heat and warm ourselves with water. Water will be the coal of the future."

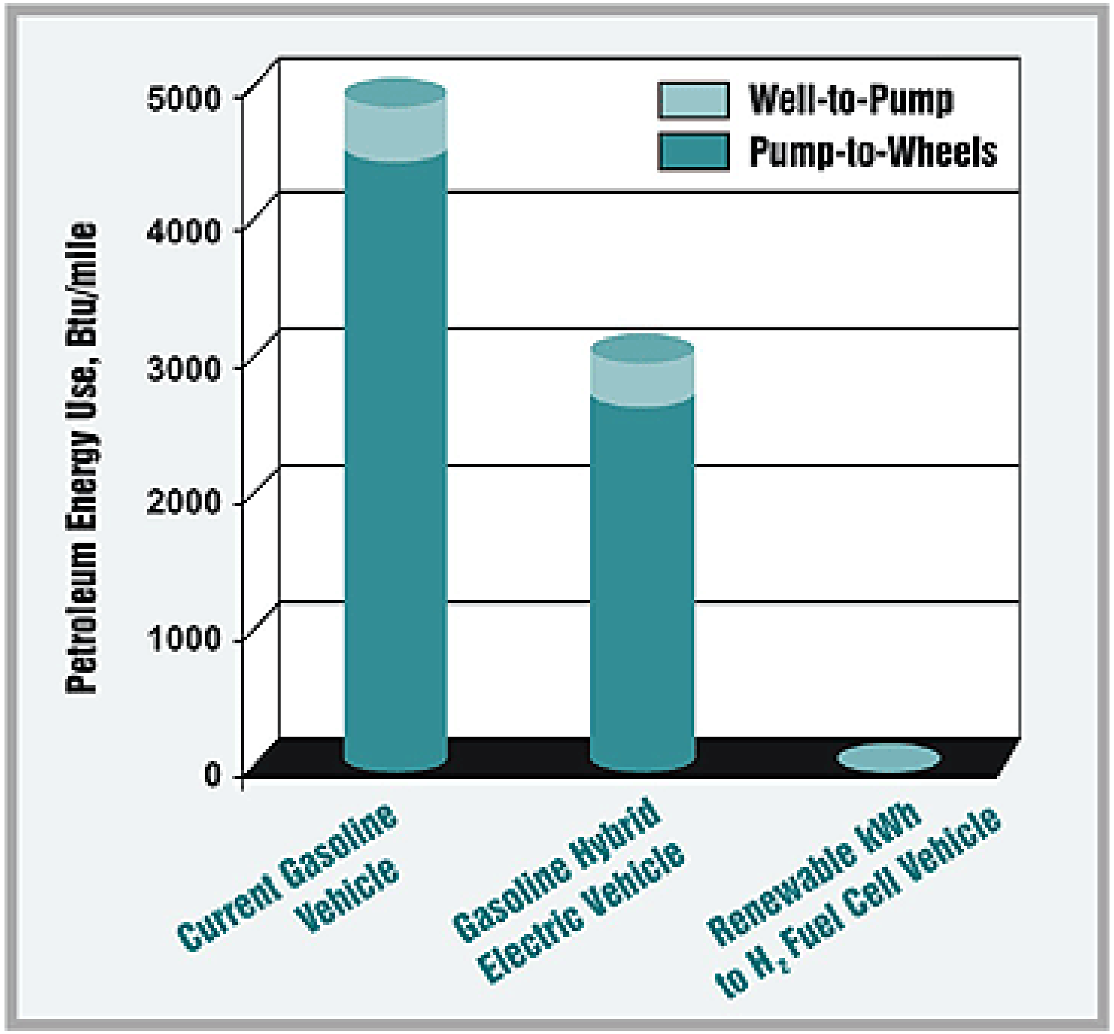
Jules Vernes (1870) "L´île mystérieuse"

Introduction

A number of countries consider Hydrogen to be a potential Long-term solution to energy security and environmental and economics concerns.
However, to achieve this hydrogen future, international collaborations In all areas of hydrogen energy development, from research to technology validation To implementation, are essential.

Setaram instrumentation offers a wide set of instruments to help speeding up this development

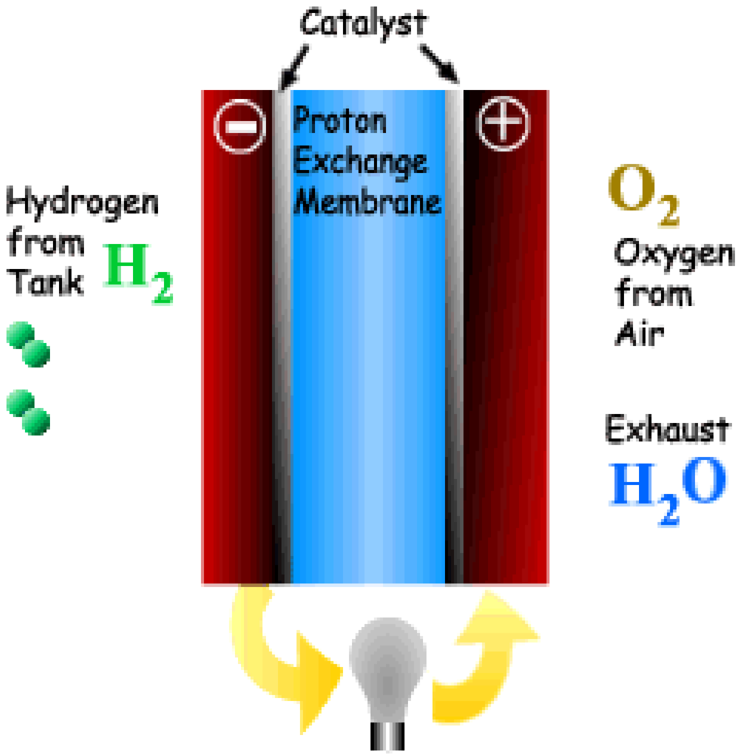
Efficiency


Petroleum Energy Use, Btu/mile
5000
4000
3000
2000
1000
0
Well-to-Pump
Pump-to-Wheels
Current Gasoline Vehicle
Gasoline Hybrid Electric Vehicle
Renewable kWh to H₂ Fuel Cell Vehicle

Fuel Cells basics

In principle, a fuel cell operates like a battery. Unlike a battery, a fuel cell does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied.
A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat.

Hydrogen fuel is fed into the "anode" of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons create a separate current that can be utilized before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water.



Fuel Cells basics

Fuel cells

Micro Fuel Cells for PDA

Motorola Fuel cell phone

DaimlerChrysler Necar 5

Applications

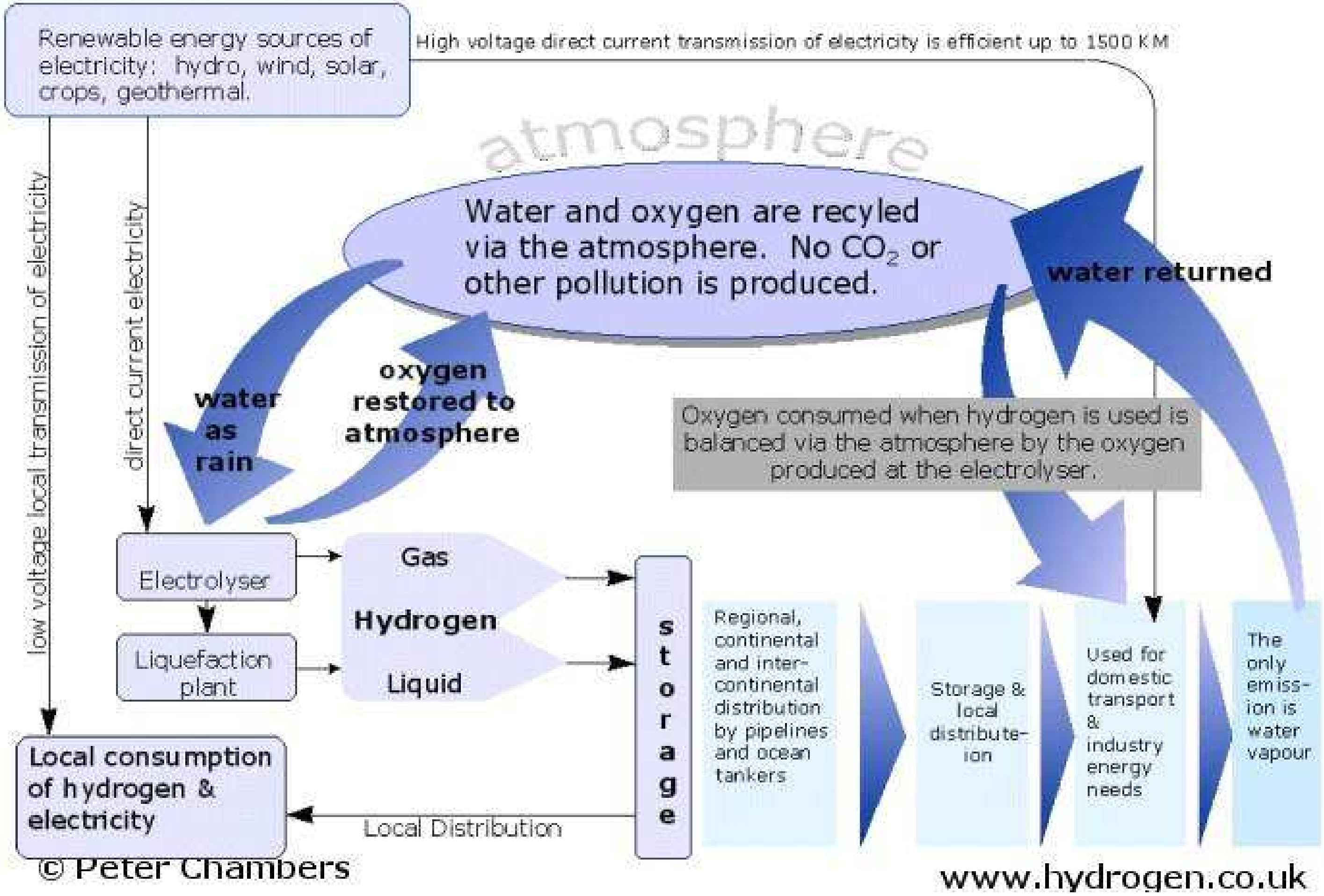
- Stationary applications
  - Transportable devices to provide electricity on a dedicated site
  - Safety power (hospital, networks, defense…)
  - Electricity for isolated sites
  - Power for industrial processes
- Portable applications
  - Portable PC
  - Mobile phones
  - Digital equipments
  - Portable electrical tools
- Inbedded applications
  - Space
  - Transportation
  - Defense
  - Bike, scooter, boat
  - Car

Fuel cells – vehicle filling station

Hydrogen basics

- Fuel cells run on hydrogen, the simplest element and most plentiful gas in the universe. Hydrogen is colorless, odorless and tasteless. Hydrogen is the lightest element, with a density of 0.08988 grams per liter at standard pressure, yet it has the highest energy content per unit weight of all the fuels – 52,000 Btu/lb, or three times the energy of a pound of gasoline.
- Hydrogen is never found alone on earth — it is always combined with other elements such as oxygen and carbon. Hydrogen can be extracted from virtually any hydrogen compound and is the ultimate clean energy carrier. It is safe to manufacture. And hydrogen's chemical energy can be harnessed in pollution-free ways.
- Hydrogen is the perfect companion to electrons in the clean energy systems of the future.

Hydrogen Energy system



Renewable energy sources of electricity: hydro, wind, solar, crops, geothermal.

High voltage direct current transmission of electricity is efficient up to 1500 KM

Water and oxygen are recyled via the atmosphere. No CO_2 or other pollution is produced.

Oxygen consumed when hydrogen is used is balanced via the atmosphere by the oxygen produced at the electrolyser.

Local consumption of hydrogen & electricity

Regional, continental and inter-continental distribution by pipelines and ocean tankers

Storage & local distribute-ion

Used for domestic transport & industry energy needs

The only emiss-ion is water vapour

© Peter Chambers

www.hydrogen.co.uk

Hydrogen fuel

How much will Hydrogen fuel cost?

The U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies Program is working to achieve the following goals:

By 2005, the technology will be available to produce hydrogen at the pump for $3.00 per gallon gasoline equivalent, and DOE wants to validate this technology by 2008.

By 2010, the price goal is $1.50 per gallon of gasoline equivalent (untaxed) at the station.

Even $3 a gallon would save most of us money, since FCVs will be two to three times more efficient than internal combustion engine (ICE) vehicles. If all the goals are met, FCVs offer the promise of energy at $1 a gallon - or less!

Hydrogen and Fuel cells

- **International Energy Agency Hydrogen Program** (http://www.ieahia.org/)
  - **Hydrogen— now mainly used as a chemical for upgrading fossil-based energy carriers— will increasingly become an energy carrier itself.**
  - **Significant use of hydrogen will contribute to the reduction of energy-linked environmental impacts, including global warming**
  - **Hydrogen has the potential for short-, medium-, and long-term applications**
  - **Hydrogen can assist in the development of renewable and sustainable energy sources by providing an effective means of storage, distribution, and conversion**
  - **Hydrogen can be produced as a storable, clean fuel from the world's sustainable nonfossil primary energy sources—solar energy, wind energy, hydropower, biomass, geothermal, nuclear, or tidal.**
  - **Hydrogen energy systems have potential value for locations where a conventional energy supply infrastructure does not exist.**

The Hydrogen Posture Plan (USA)

- In his 2003 State of the Union address, President Bush announced a $1.2 billion hydrogen initiative to reverse America's growing dependence on foreign oil and reduce greenhouse gas emissions. The President urged the development of commercially viable hydrogen fuels and technologies for cars, trucks, homes, and businesses.

  «With a new national commitment, our scientists and engineers will overcome obstacles…so that the first car driven by a child born today could be powered by hydrogen, and pollution-free.

  President Bush,State of the Union Address, January 28, 2003

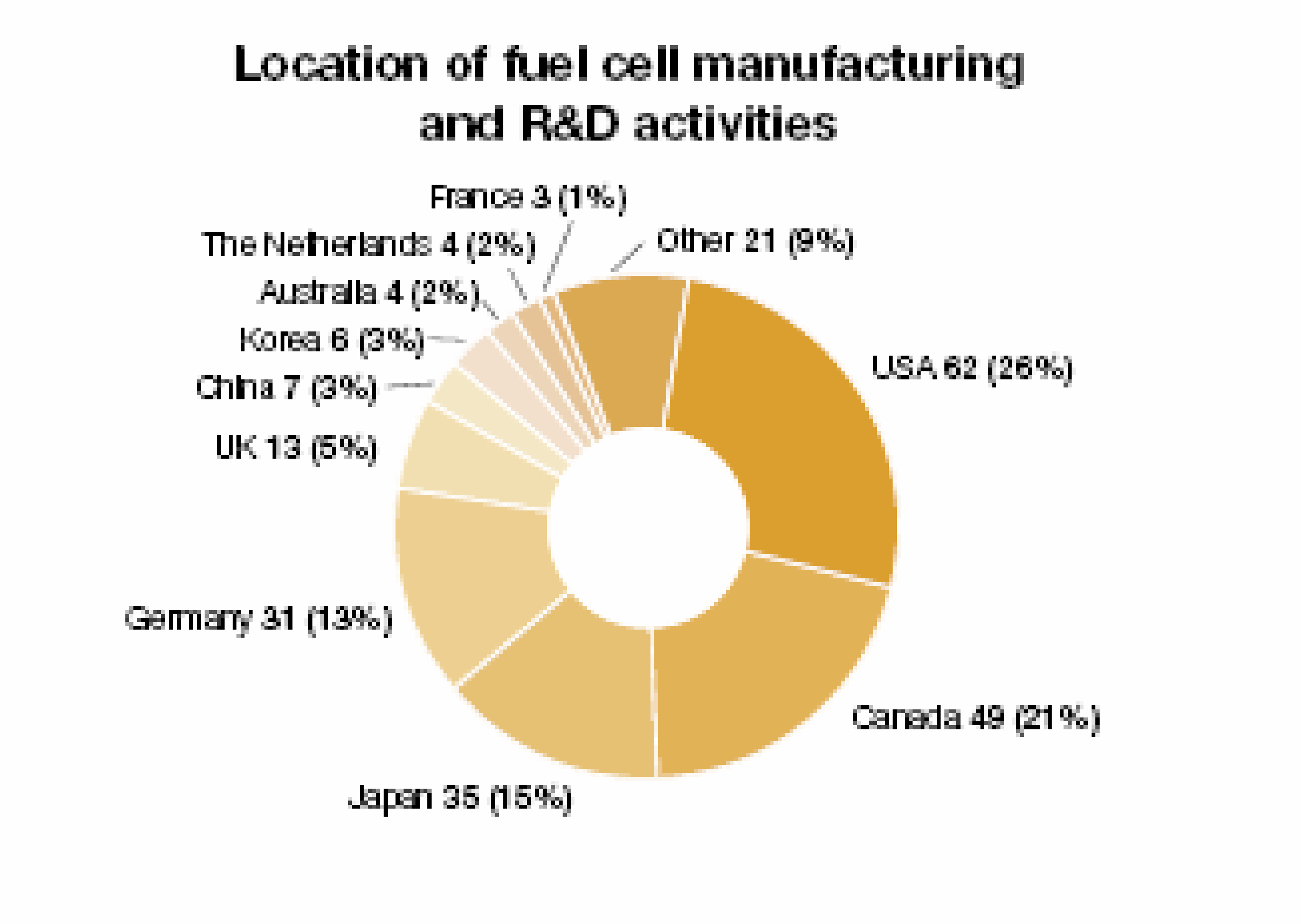
- The National Academies' report (February 2004) on the DOE hydrogen program concludes that:

  « A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy resources for hydrogen production while reducing environmental impacts, including atmospheric CO2 emissions and criteria pollutants. »

Fuel cell market size

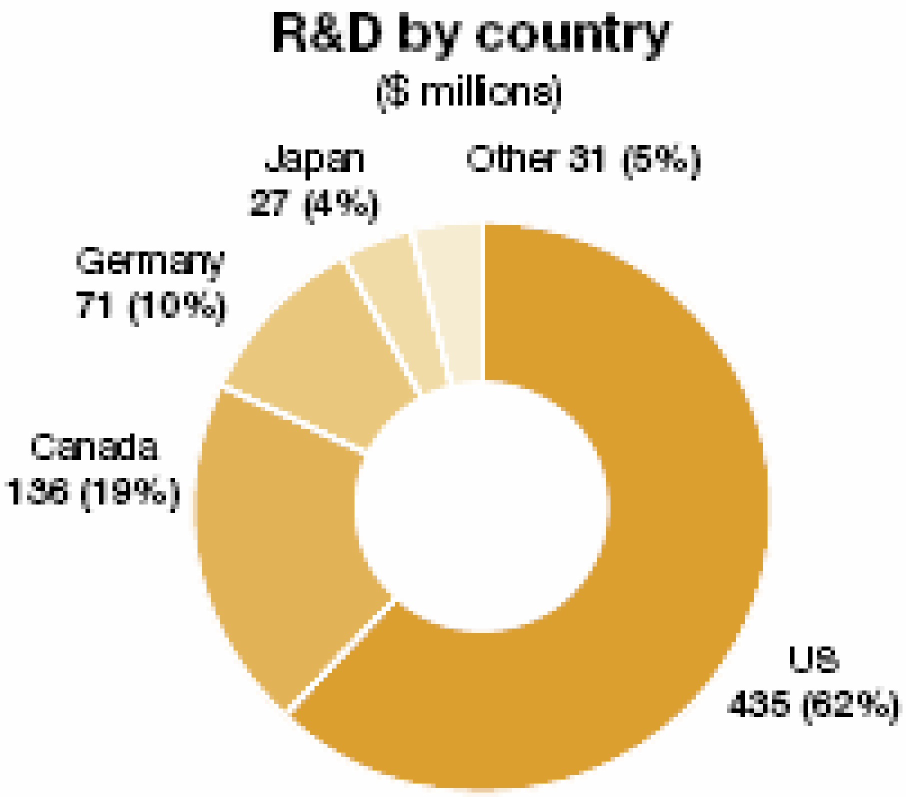
- Clean Edge (USA) in march 2006
  - 15,1 milliards USD in 2015
- Fuji-Keizai (Japan) in november 2005
  - 13 milliards USD in 2020 (with 9 milliards USD in transportation)
- PriceWaterHouseCoopers (USA) in june 2002
  - 46 milliards USD in 2011

Region of Development



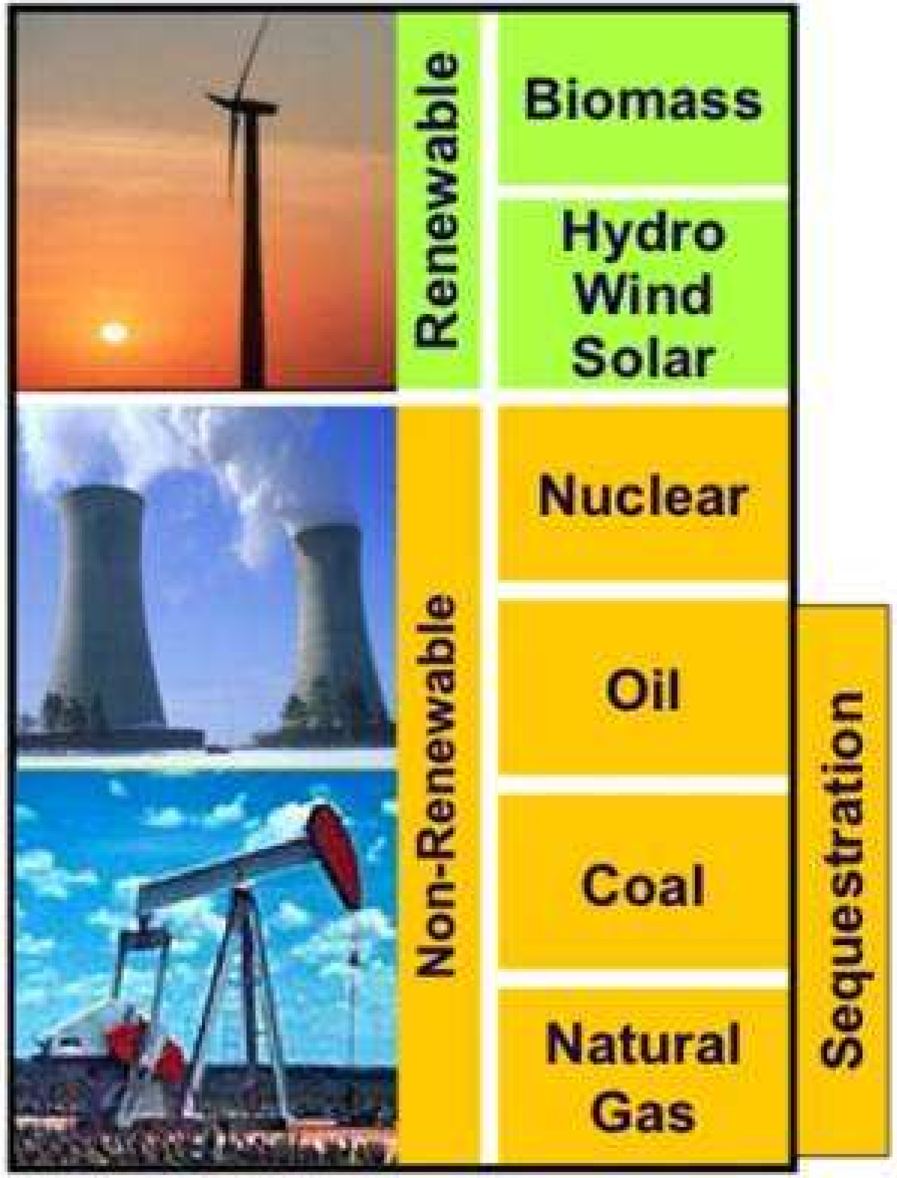
2005 Worldwide Fuel Cell Industry Survey

R&D by country

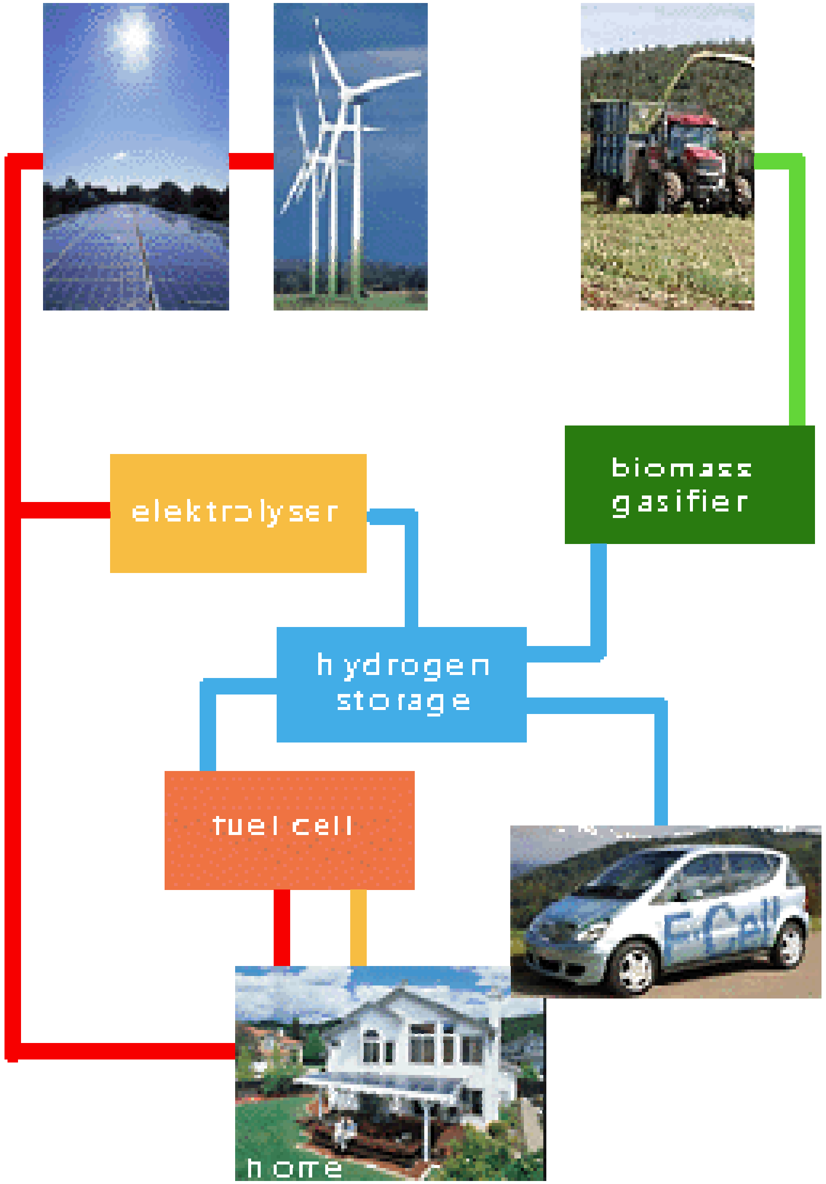


2005 Worldwide Fuel Cell Industry Survey

Sources for hydrogen production



From hydrogen production to Fuel Cells



elektrolyser

biomass gasifier

hydrogen storage

fuel cell

Different types of fuel cells

Type	**Power**	**Working temperature**	**Electrical efficiency**	**Applications**
Polymer Exchange Membrane Fuel Cell (PEMFC)	1 We to 250 kWe	60 to 80℃	35 to 40%	Portables Transportation Stationary
Direct Methanol Fuel Cell (DMFC)	100 mWe to 100kWe	60 to 90℃	10 to 30%	Portables Transportation Maritime
Alkaline Fuel Cell (AFC)	10 to 50 kWe	50 to 250℃	40%	Space Transportation
Phosphoric Acid Fuel Cell (PAFC)	100 to 200 kWe	160 to 220℃	40%	Transportation Stationary
Molten Carbonate Fuel Cell (MCFC)	100 kWe to 2 MWe	650℃	45 to 50%	Stationary
Solid Oxid Fuel Cell (SOFC)	1 kWe to some MWe	750 to 1050℃	45 to 50%	Stationary

Production of Hydrogen

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Hydrogen Energy Infrastructure

- **PRODUCTION**
  From fossil fuels, biomass, or water involves thermal, electrolytic, and photolytic processes

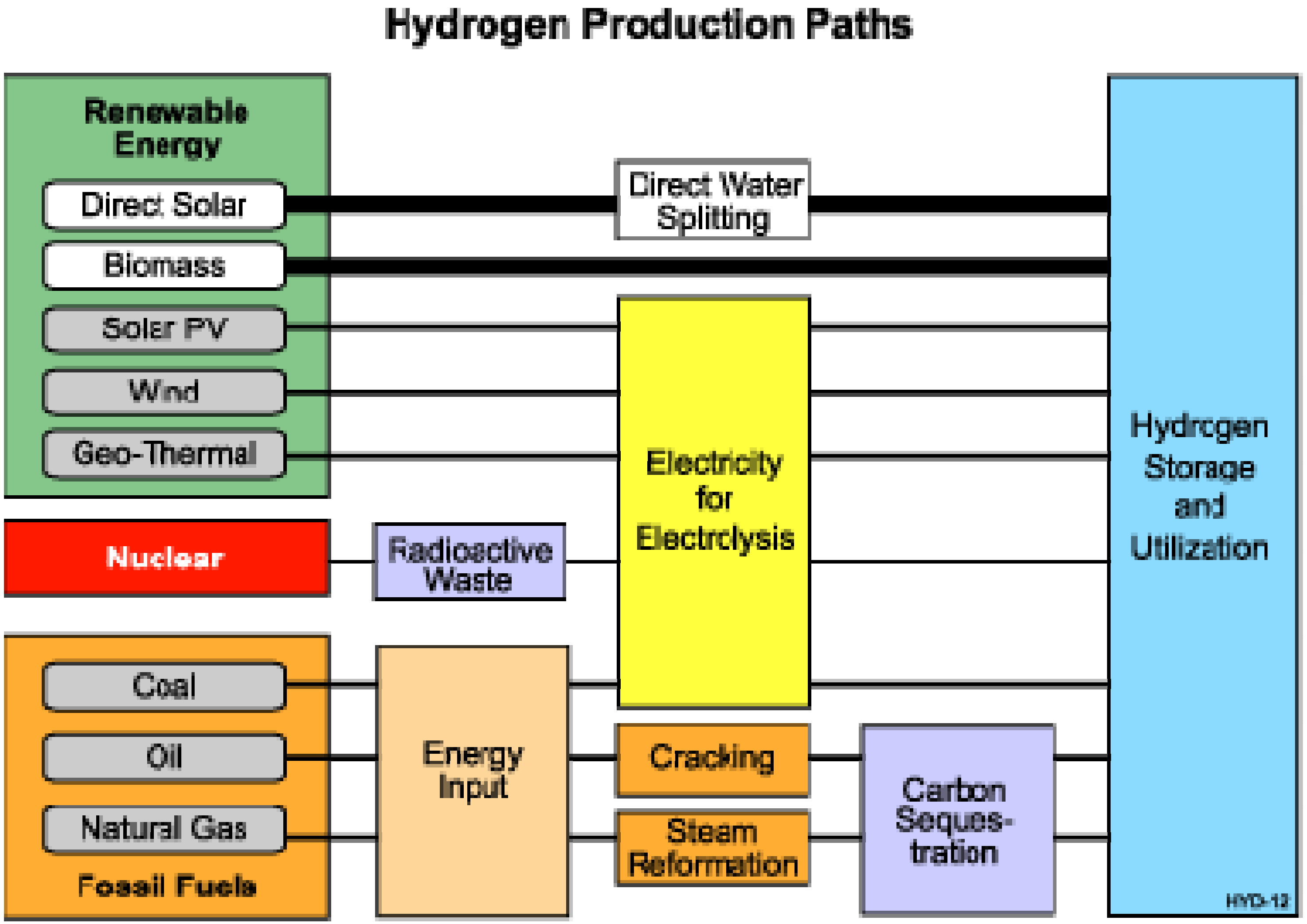
- **DELIVERY**
  Pipelines, trucks, rail and barges, requires efficient reversible solid or liquid carrier systems

- **STORAGE**
  Tanks for both gases and liquids at ambient and high pressures,
  Reversible and irreversible solid- and liquid-state, systems, including metal and chemical hydrides

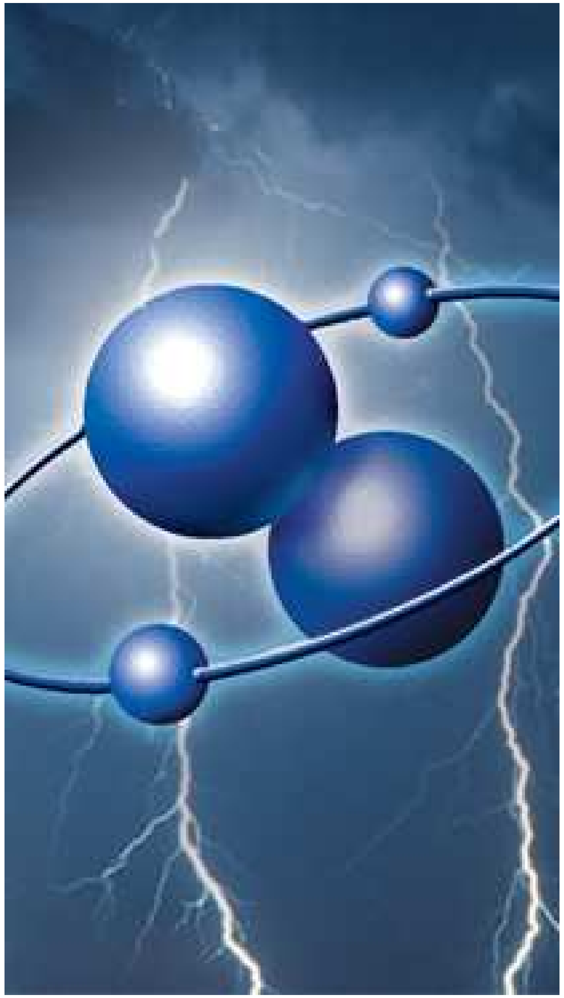
- **CONVERSION**
  Combustion turbines, reciprocating engines, and fuel cells

- **END USE ENERGY APPLICATIONS**
  Fuel-cell vehicles, internal combustion engines, and for portable power devices

PRODUCTION OF HYDROGEN



PRODUCTION OF HYDROGEN From Fossil Fuel



- Steam reforming (steam methane reforming SMR) @ 800℃/3-25 bars

$CH_4 + H_2O + heat \rightarrow CO + 3H_2$
$CO + H_2O \rightarrow CO_2 + \mathbf{H_2} + heat$

- Partial oxidation (POX).

$CH_4 + 1/2O_2 \rightarrow CO + 2H_2 + heat$
$CO + H_2O \rightarrow CO_2 + \mathbf{H_2} + heat$

In this process, heat is produced in an exothermic reaction, and hence a more compact design is possible as there is no need for any external heating of the reactor.

- Autothermal reforming (ATR).

Combination of both steam reforming and partial oxidation

The total reaction is exothermic, and so it releases heat. The outlet temperature from the reactor is in the range of 950 to 1100 ℃, and the gas pressure can be as high as 100 bar. The need to purify the output gases adds significantly to plant costs and reduces the total efficiency.

PRODUCTION OF HYDROGEN From Coal

Through a variety of gasification processes (e.g. fixed bed, fluidised bed or entrained flow).

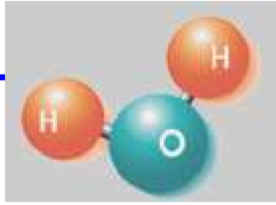
In practice, high-temperature entrained flow processes are favoured to maximise carbon conversion to gas, thus avoiding the formation of significant amounts of char, tars and phenols.

Typical reaction :

$$C(s) + H_2O + \text{heat} \rightarrow CO + H_2$$

Since this reaction is endothermic, additional heat is required, as with methane reforming.

PRODUCTION OF HYDROGEN From Splitting of Water



- Water electrolysis

H_2O + electricity → $H_2 + 1/2O_2$

- Alkaline electrolysis

Use an aqueous KOH solution (caustic) as an electrolyte

Suited for stationary applications - operating pressures up to 25 bar.

Mature technology

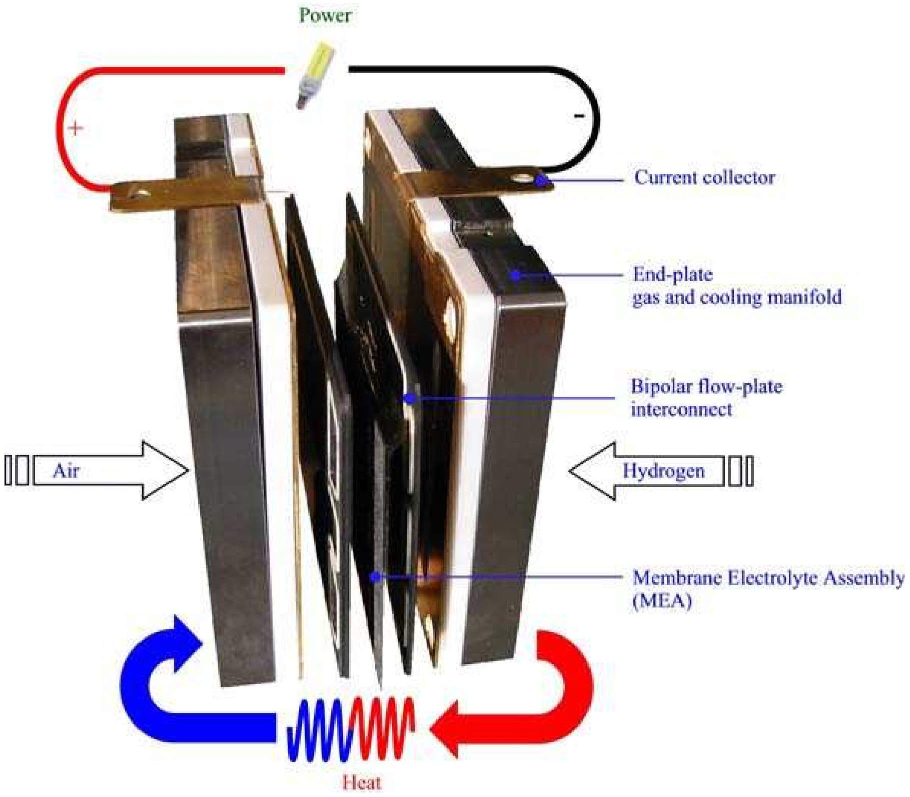
- Polymer Electrolyte Membrane electrolysis

Require no liquid electrolyte,→ Design simplified. Electrolyte : acidic polymer membrane. Operating pressure up to ~100 bars

Application in stationary and mobile applications.

Drawback : limited lifetime of the membranes.

Advantages : higher turndown ratio, the increased safety due to the absence of KOH electrolytes, a more compact design due to higher densities, and higher operating pressures.



PRODUCTION OF HYDROGEN From Splitting of Water

- high-temperature water decomposition.

Electrical energy needed to split water at 1000 °C << electrolysis at 100 °C.
→Higher overall process efficiencies than regular low-temperature electrolysers.

Typical technology is the solid oxide electrolyser cell (SOEC). This electrolyser is based on the solid oxide fuel cell (SOFC), which normally operates at 700 to 1000 °C.
→ Electrode reactions : reversible

Main R&D needs for SOECs : materials development and thermo-mechanical stress within the functional ceramic materials.

Main technical issues : materials development for corrosion resistance at high temperatures, high-temperature membrane and separation processes, heat exchangers, and heat storage media.

Design aspects and safety are also important for high-temperature processes.

solid oxide fuel cell (SOFC)

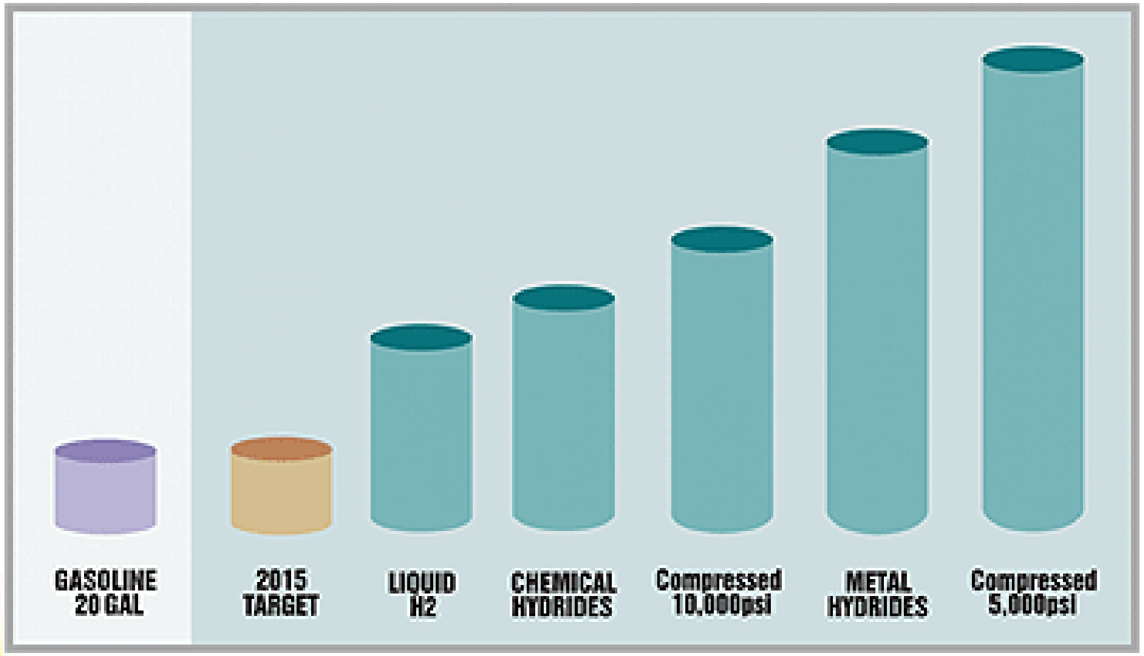
PRODUCTION OF HYDROGEN From Biomass

In biomass conversion processes, a hydrogen-containing gas is normally produced in a manner similar to the gasification of coal.

Biomass gasification is an R&D area shared between H2 production and biofuels production.

Gasification and pyrolysis are considered the most promising medium-term technologies for the commercialisation of H2 production from biomass.

Hydrogen Storage



HYDROGEN STORAGE

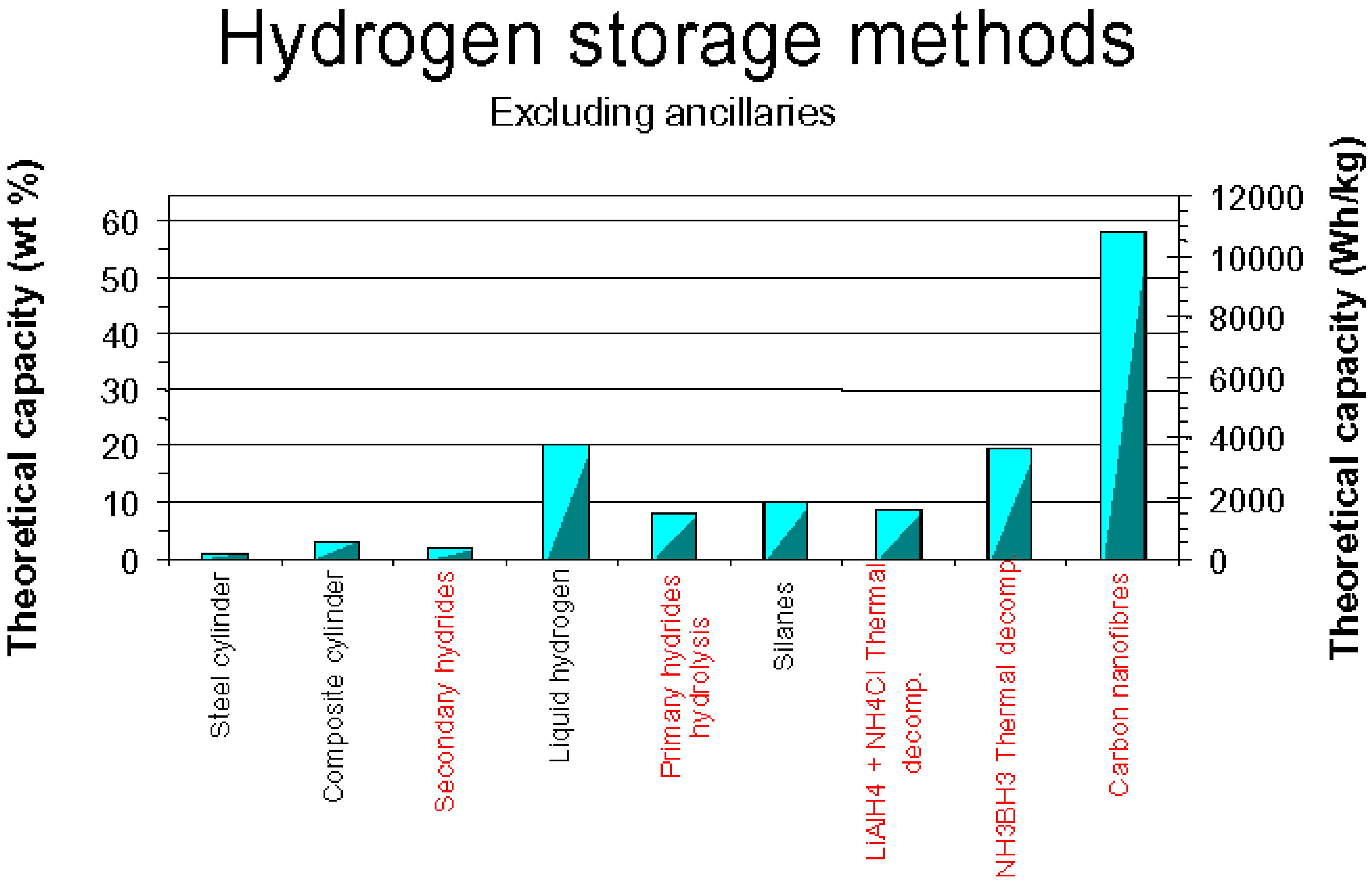
Three principal forms of hydrogen storage :

- gas
- liquid
- solid

Technical issues :

weight, volume, discharge rates, heat requirements, recharging time.. And cost

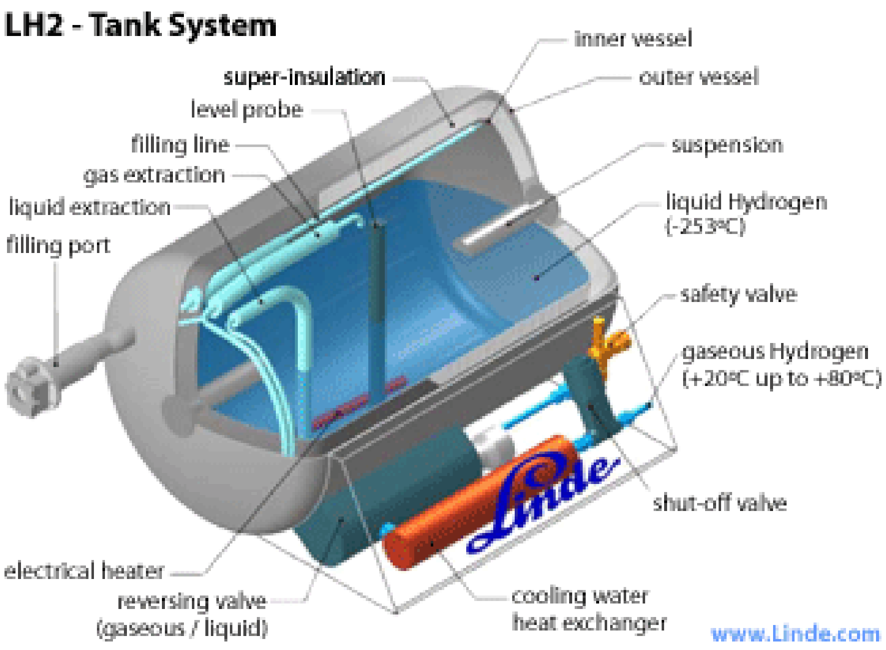
HYDROGEN STORAGE



HYDROGEN STORAGE GASEOUS

The most common method to store hydrogen in gaseous form is in steel tanks, although lightweight composite tanks designed to endure higher pressures are also becoming more and more common.

Cryogas, gaseous hydrogen cooled to near cryogenic temperatures, is another alternative that can be used to increase the volumetric energy density of gaseous hydrogen. A more novel method to store hydrogen gas at high pressures is to use glass microspheres.



HYDROGEN STORAGE LIQUID

Cryogenic Liquid hydrogen (CLH2)

Much better energy density than the pressurised gas solutions at relatively low pressures. Liquid hydrogen has been demonstrated in commercial vehicles (particularly by BMW), and in the future it could also be co-utilized as aircraft fuel, since it provides the best weight advantage of any H_2 storage.

Main disadvantage : boil-off loss during dormancy, and need for super-insulated cryogenic containers.

$NaBH_4$ (Borohydrides) solutions

$NaBH_4$ (l) + $2H_2O$ (l) → $4H_2$ (g) + $NaBO_2$ (s) (ideal reaction)
The theoretical maximum hydrogen energy storage density for this reaction is 10.9 wt.% H_2
Main disadvantage : $NaBO_2$ must be regenerated back to $NaBH_4$.

Rechargeable organic liquids

dehydrogenation and hydrogenation of methylcyclohexane (C_7H_{14}) and toluene (C_7H_8):

C_7H_{14} (l) ⇔ C_7H_8 (l) + 3 H_2 (g) (*T*dehyd = 300-400 °C)

HYDROGEN STORAGE SOLID

Storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications.

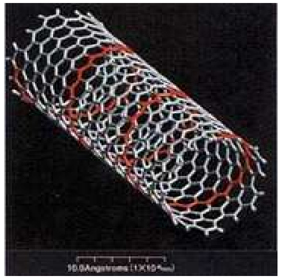
There are four main groups of suitable materials:

- carbon and other high surface area materials
- H_2O-reactive chemical hydrides
- thermal chemical hydrides
- rechargeable hydrides.

Carbon and other high surface area materials

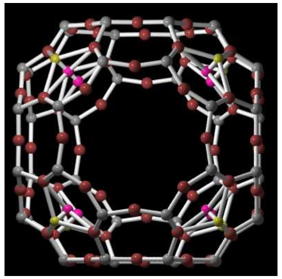
Carbon-based materials (nanotubes and graphite nanofibers)

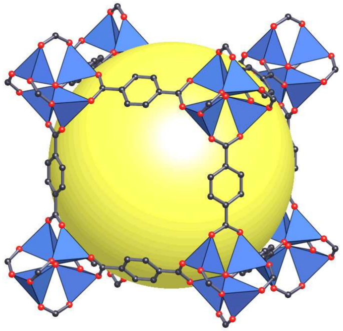
- Pure H_2 molecular physisorption has been clearly demonstrated, but is useful only at cryogenic temperatures (up to ca. 6 wt.% H_2), and extremely high surface area carbons are required. Pure atomic H-chemisorption has been demonstrated to ca. 8 wt.% H_2, but the covalent-bound H is liberated only at impractically high temperatures (above ca. 400 ℃).


Carbon nanotubes

Other high surface area materials

- *Zeolites:* Complex aluminosilicates with engineered pore sizes and high surface areas. Well known as “molecular sieves”. The science for capturing non-H2 gases is well known.
- *Metal oxide frameworks (MOFs):* Typically ZnO structures bridged with benzene rings. These materials have an extremely high surface area, are highly versatile and allow for many structural modifications.
- *Clathrate hydrates:* H_2O (ice) cage


Zeolites


Metal Oxides Frameworks

R&D Question?

Materials : extremely high surface areas that can physisorb molecular H_2 (few wt.% H_2 at cryogenic temperatures.)

Reversible storage of high levels of H_2 near room temperature??

New metal oxide frameworks and clathrate hydrates represents new storage ideas

Rechargeable Materials

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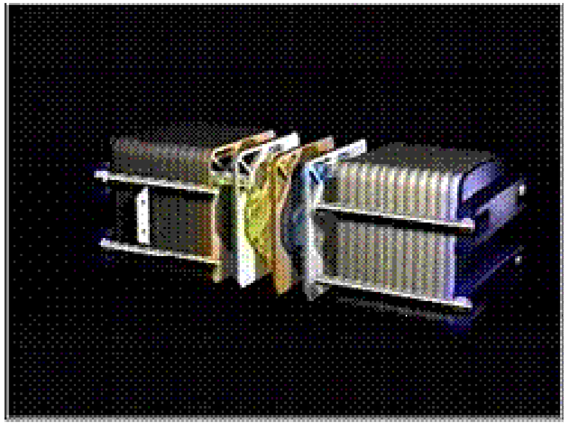


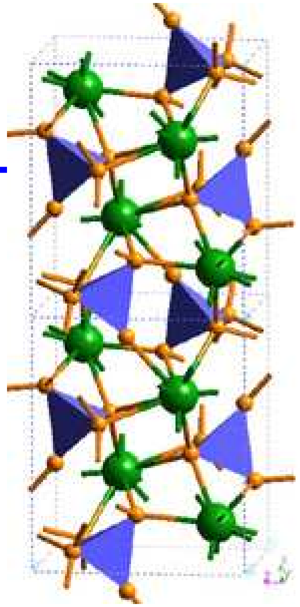
(CNN)

Rechargeable hydrides

R&D on rechargeable hydrides has been going on for decades, and a large database with information about their properties exists today (http://hydpark.ca.sandia.gov). It becomes clear that the complex hydrides provide the hope for the future, particularly the non-transition metal types such as:

- borohydrides
- alanates
- amides.

Rechargeable hydrides : Alanates



- Ex : $NaAlH_4$. Low-temperature kinetics and reversibility improved by adding a catalyst (*e.g.* Ti).. However, with only ca. 4-5 reversible wt. % H2, $NaAlH_4$ cannot meet weight targets and has potential problems with pyrophoricity and cost.

- The main R&D task is to extend the catalyst concept to other alanates beyond $NaAlH_4$.

Type	**Storage density*, wt.% H2**	**Desorption temperature, °C**
LiAlH4	10.6	190
NaAlH4	7.5	100
Mg(AlH4)	9.3	140
Ca(AlH4)	7.8	> 230

Rechargeable hydrides : Borohydrides

- Much higher potential capacities and safer than the alanates.
- But are too stable, and not as reversible as alanates
- Recent progress on $LiBH_4$, particularly on reversibility and destabilisation.

Type Storage	**density*, wt.% H2**	**Desorption temperature, °C**
$LiBH_4$	18.5	300
$NaBH_4$	10.6	350
KBH_4	7.4	125
$Be(BH_4)_2$	20.8	125
$Mg(BH_4)_2$	14.9	320
$Ca(BH_4)_2$	11.6	260

Rechargeable hydrides : Chemical hydrides (H2O-reactive)

- Chemical hydrides can be handled in a semi-liquid form, such as mineral oil slurry. In this form, hydrides can be pumped and safely handled. Controlled injection of H_2O during vehicle operation is used to generate H_2 via hydrolysis reactions.

Hydrolysis reaction	**Storage density*, wt.% H_2**
$LiH + H_2O \Rightarrow H_2 + LiOH$	7.8
$NaH + H_2O \Rightarrow H_2 + NaOH$	4.8
$MgH_2 + 2H_2O \Rightarrow 2H_2 + Mg(OH)_2$	6.5
$CaH_2 + 2H_2O \Rightarrow 2H_2 + Ca(OH)_2$	5.2

Rechargeable hydrides :Chemical hydrides (thermal)

- Ammonia borane.. However, the reactions are not reversible, and off-board regeneration is required.

Type Storage	**density*, wt.% H2**	**Desorption temperature, ℃**
$NH_4BH_4 \Rightarrow NH_3BH_3 + H_2$	6.1	< 25
$NH_3BH_3 \Rightarrow NH_2BH_2 + H_2$	6.5	< 120
$NH_2BH_2 \Rightarrow NHBH + H_2$	6.9	> 120
$NHBH \Rightarrow BN + H_2$	7.3	> 500

(Tom Autrey, PNNL: results obtained with C80 for steps 2 and 3)

Hydrogen storage comparison

- **Gaseous H_2 Storage:**
  Status: Commercially available, but costly.
  Best option: C-fibre composite vessels (6-10 wt% H_2 at 350-700 bar).
  R&D issues: Fracture mechanics, safety, compression energy, and reduction of volume.

- **Liquid H_2 Storage:**
  Status: Commercially available, but costly.
  Best option: Cryogenic insulated dewars (ca. 20 wt% H_2 at 1 bar and -253°C).
  R&D issues: High liquefaction energy, dormant boil off, and safety.

- **Solid H_2 Storage:**
  Status: Very early development (many R&D questions).
  Best options: Too early to determine. Many potential options: Rechargeable hydrides, chemical hydrides (H_2O &s thermally reactive), carbon, and other high surface area materials.
  Most-developed option: Metal hydrides (potential for > 8 wt.% H_2 and > 90 kg/m3 H_2-storage capacities at 10-60 bar).
  R&D issues: Weight, lower desorption temperatures, higher desorption kinetics, recharge time and pressure, heat management, cost, pyrophoricity, cyclic life, container compatibility and optimisation

Hydrogen storage comparison

- Comparisons between the three basic storage options shows that the potential advantages of solid H_2-storage compared to gaseous and liquid hydrogen storage are:
  - Lower volume .
  - Lower pressure (greater energy efficiency).
  - Higher purity H2 output.

- Compressed gas and liquid storage are the most commercially viable options today, but completely cost-effective storage systems have yet to be developed. The safety aspects with all storage options, particularly the novel hydride storage options, must not be underestimated.

Use of Setaram Instruments

SETARAM Instrumentation

KEP Technologies

SETARAM and the Hydrogen R§D

The main target for SETARAM on the Hydrogen R§D is the **solid hydrogen storage:**

- Adsorption and desorption
- Reversibility
- Storage efficiency
- Thermal cycling
- Work under normal and high pressure
- Safety

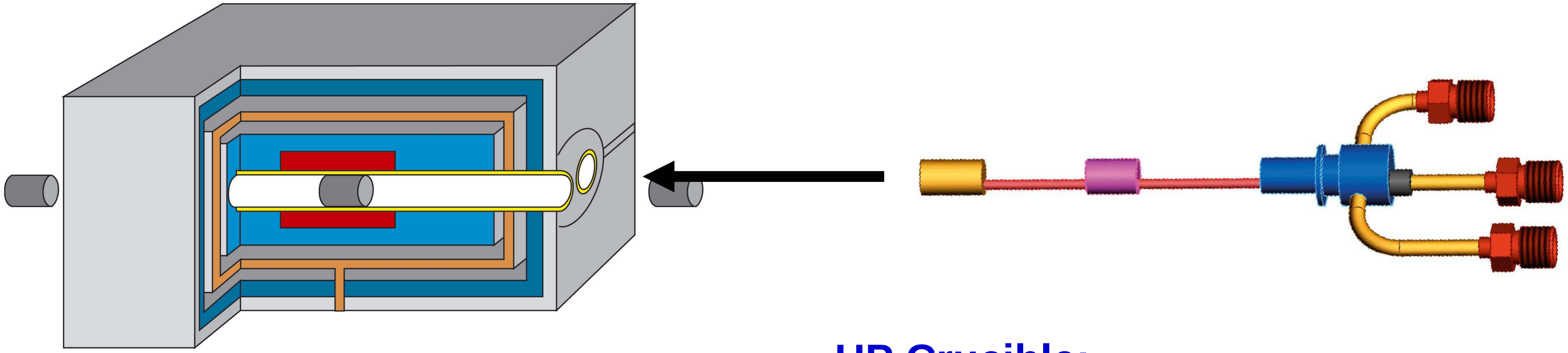
Instruments

- C80
- HP-MicroDSC VII
- Sensys (TG and DSC)

Also Multi-HTC for the characterization of electrolytes in molten carbonate and solide oxide fuel cells

Sensys DSC

3D sensor inside



HP Crucible:

P<500 bars & T<600℃

Hydriding of Ti-Mg-Ni

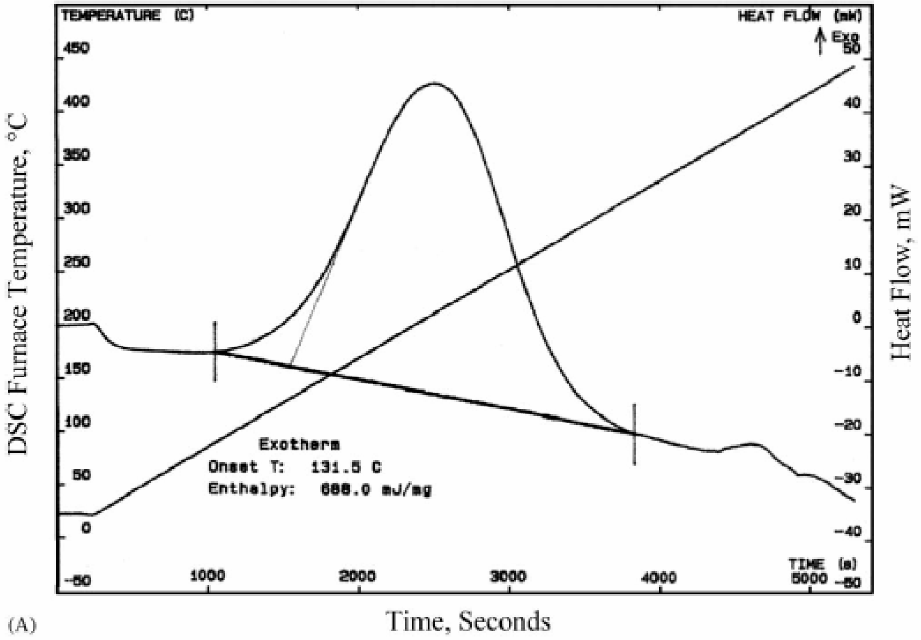
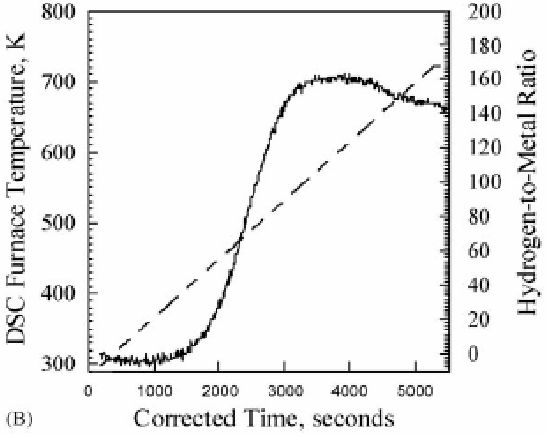


Fig. 1. (A). Thermogram for the hydriding of Ti–Mg–Ni mechanically alloyed for 44 h 20 min.



**(B) Composition–temperature curve for Ti–Mg–Ni mechanically alloyed for 44 h 20 min. The dashed line is the DSC furnace temperature and the solid line in the plot indicates
the hydrogen-to-metal ratio.**

from J.K.Lomness et al International Journal of Hydrogen Energy 27 (2002) 915-920

Dehydriding of LiAlH4

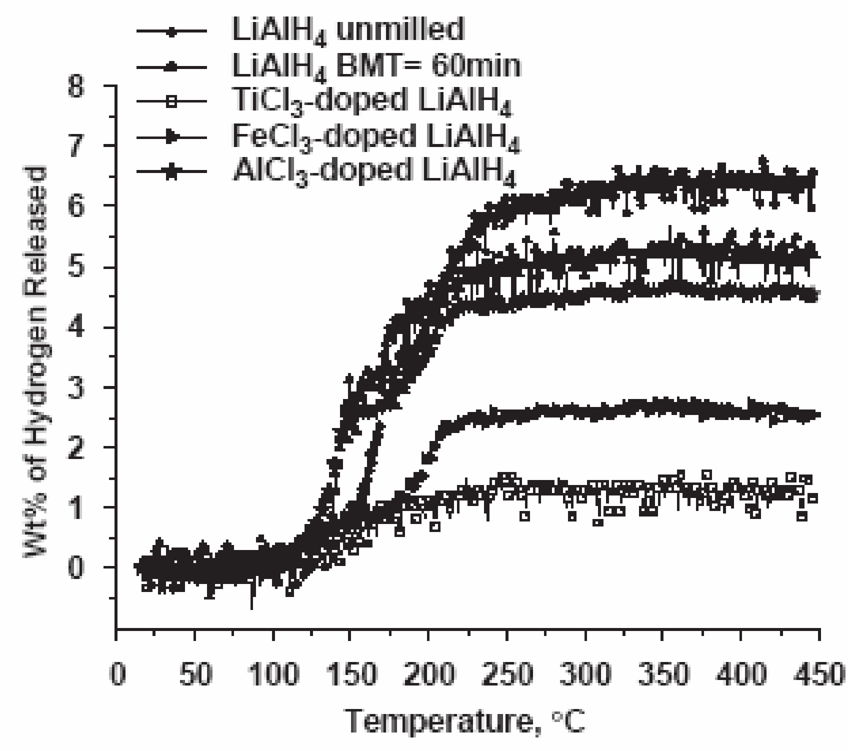
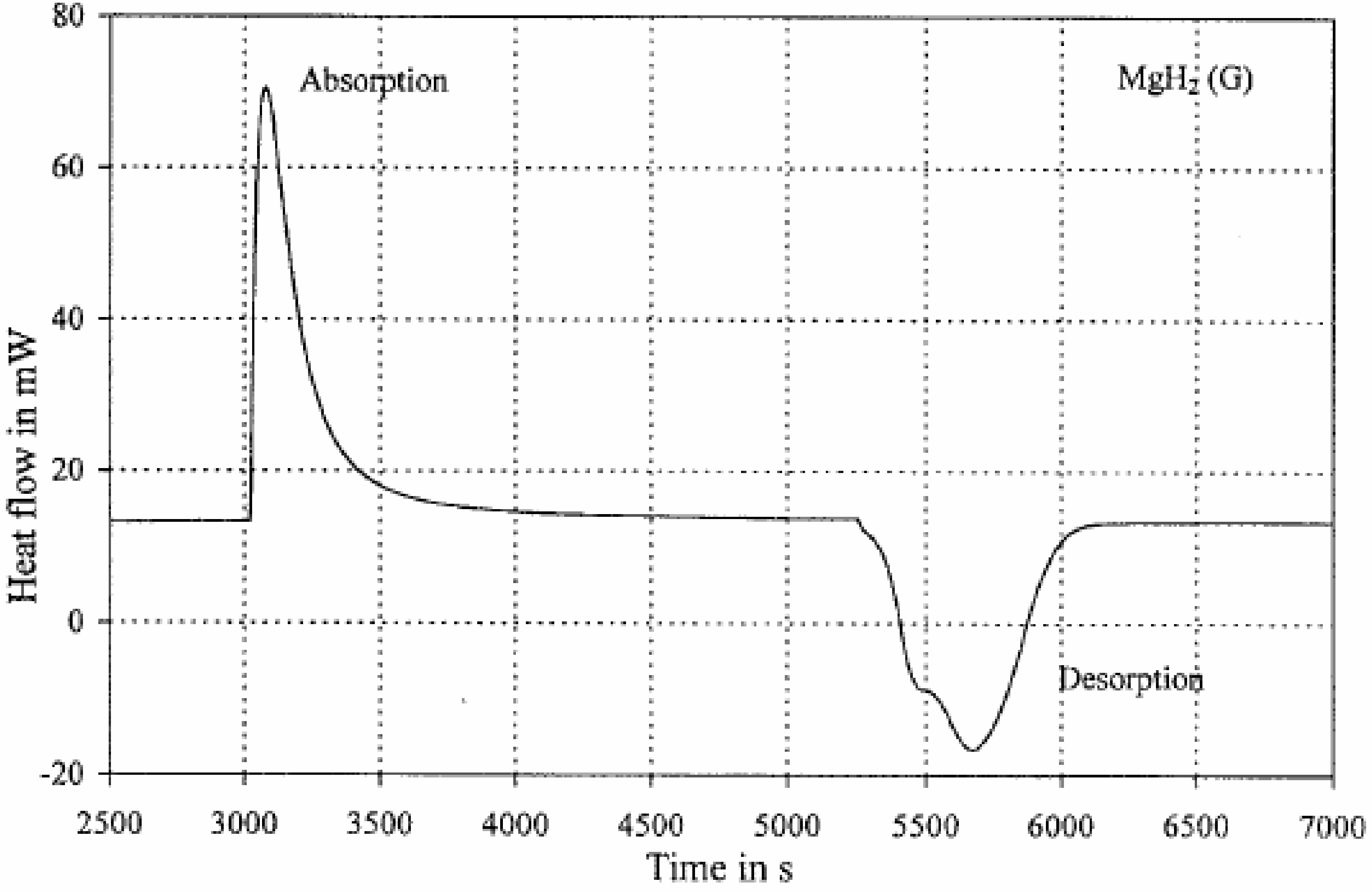


Fig. 2. DSC pressure data for dehydriding of unaltered $LiAlH_4$, ball-milled $LiAlH_4$, $LiAlH_4$ doped with $TiCl_3$, $LiAlH_4$ doped with $FeCl_3$, and $LiAlH_4$ doped with $AlCl_3$.

from M.Resan et al International Journal of Hydrogen Energy 30 (2005) 1413-1416

Hydrogenation and dehydrogenation of MgH_2 at T=Cst



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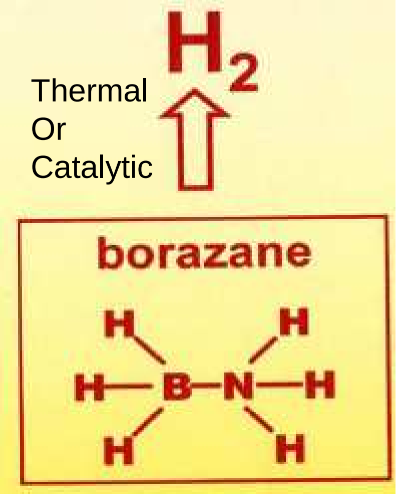
from K.Bohmhammel et al Thermochimica acta 310 (1998) 167-171

Thermal decomposition of BNH-compound and Sensys

Hydrogen storage with novel Nanomaterials

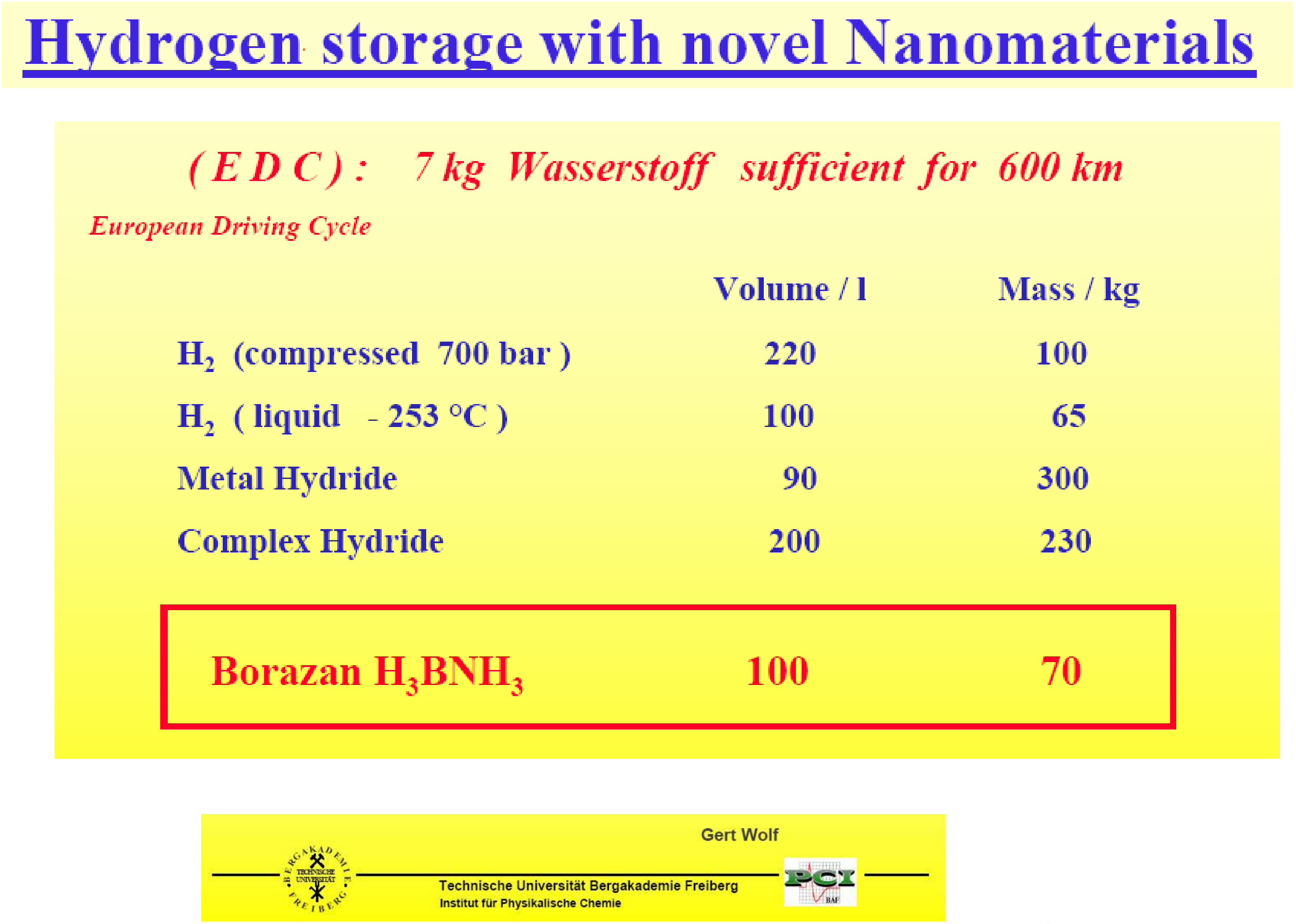


1.15 kg Hydrogen →

- 17 l H_2 (liquid -253 °C)
- 29 l H_2 (gase 700 bar)
- 12 l H_3BNH_3 (solid, 9 kg)

Gert Wolf
Technische Universität Bergakademie Freiberg
Institut für Physikalische Chemie

Thermal decomposition of BNH-compound



Hydrogen storage with novel Nanomaterials

(E D C) :   7 kg Wasserstoff   sufficient for 600 km

European Driving Cycle

	Volume / l	Mass / kg
H_2 (compressed 700 bar)	220	100
H_2 (liquid - 253 °C)	100	65
Metal Hydride	90	300
Complex Hydride	200	230
Borazan H_3BNH_3	**100**	**70**

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Technische Universität Bergakademie Freiberg
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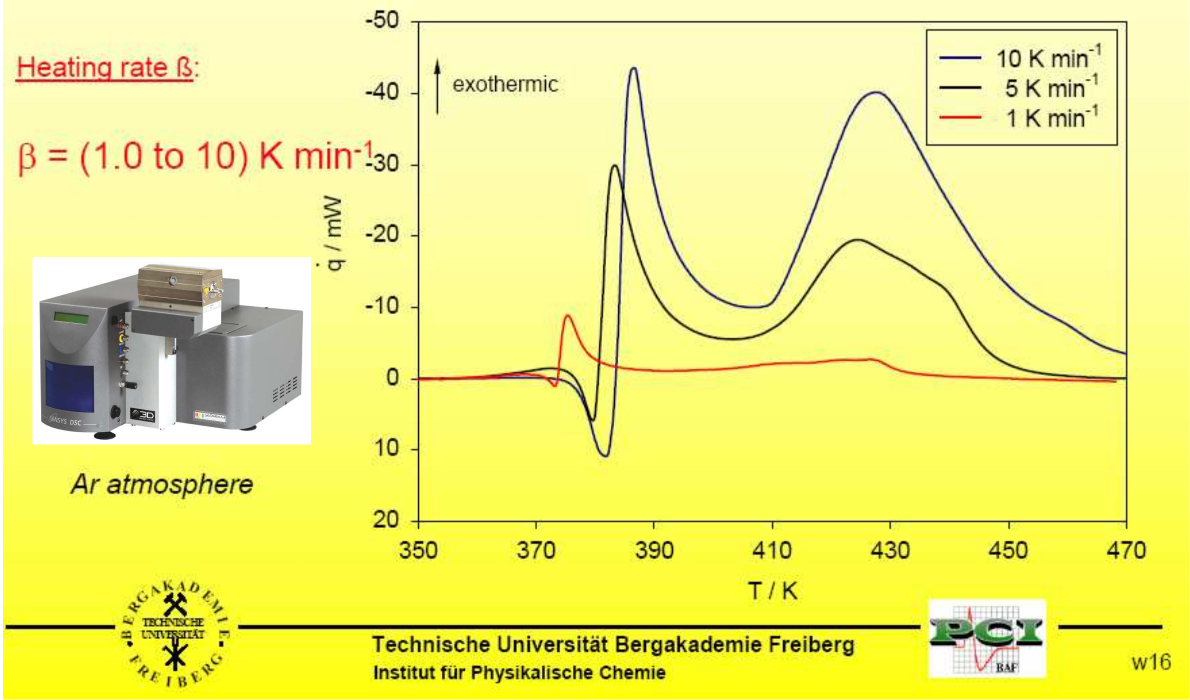
Thermal decomposition of BNH-compound

Decomposition of BH_3NH_3 dependent on the heating rate



Heating rate ß:

β = (1.0 to 10) K min^{-1}

Ar atmosphere

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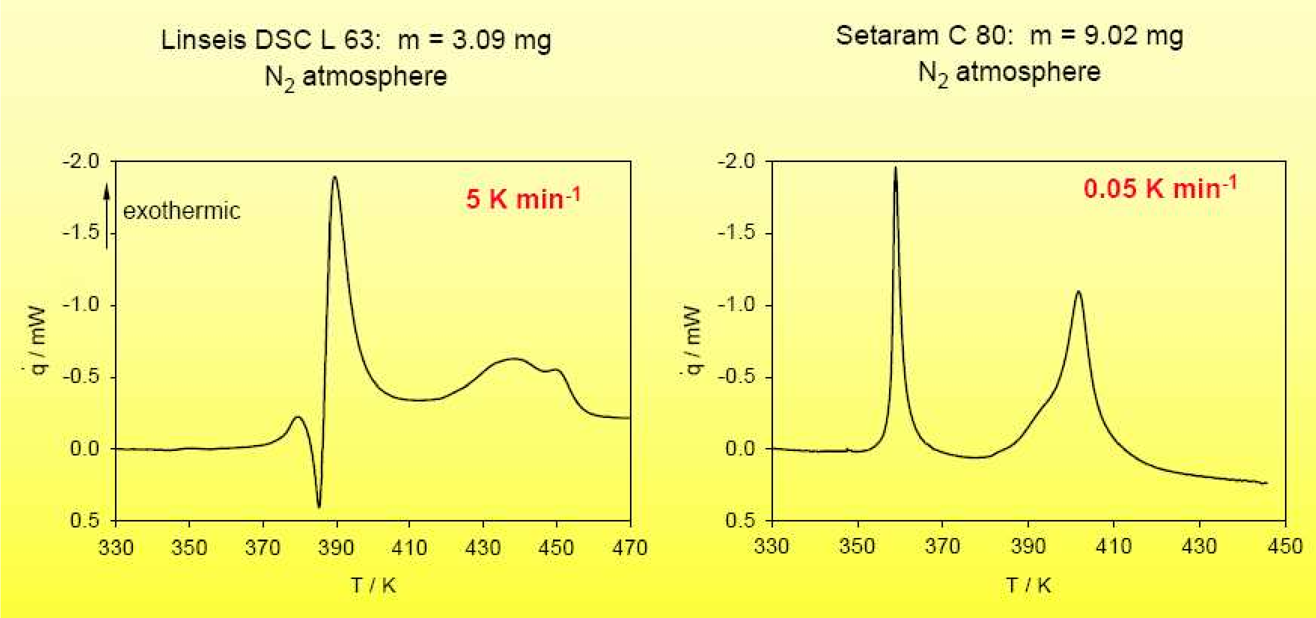
Thermal decomposition of BNH-compound

Thermal decomposition of BH_3NH_3


Linseis DSC L 63: m = 3.09 mg
N_2 atmosphere

Setaram C 80: m = 9.02 mg
N_2 atmosphere

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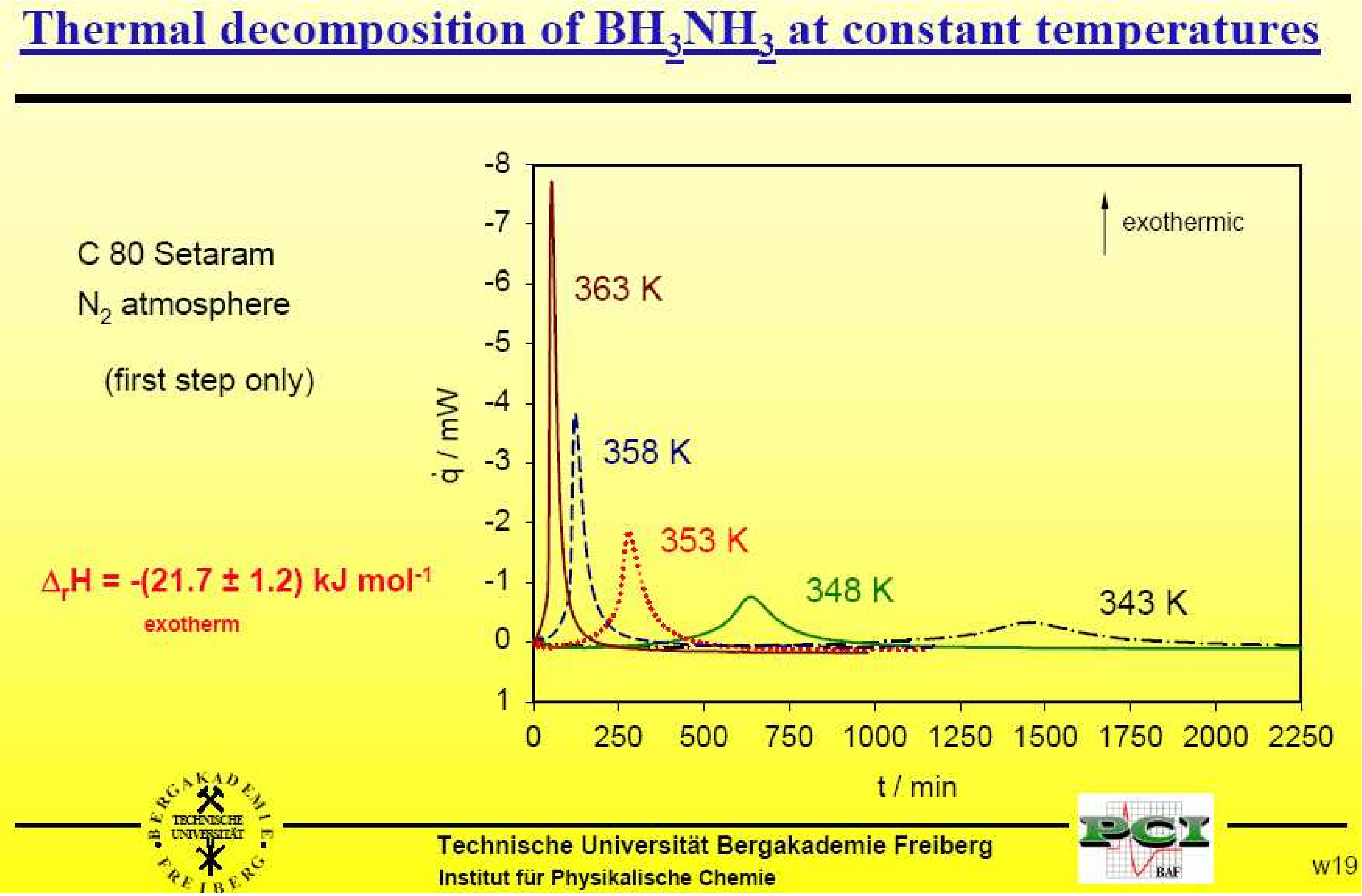
Thermal decomposition of BNH-compound



Thermal decomposition of BH_3NH_3 at constant temperatures

C 80 Setaram

N_2 atmosphere

(first step only)

$\Delta_rH = -(21.7 \pm 1.2)$ kJ mol^{-1}

exotherm

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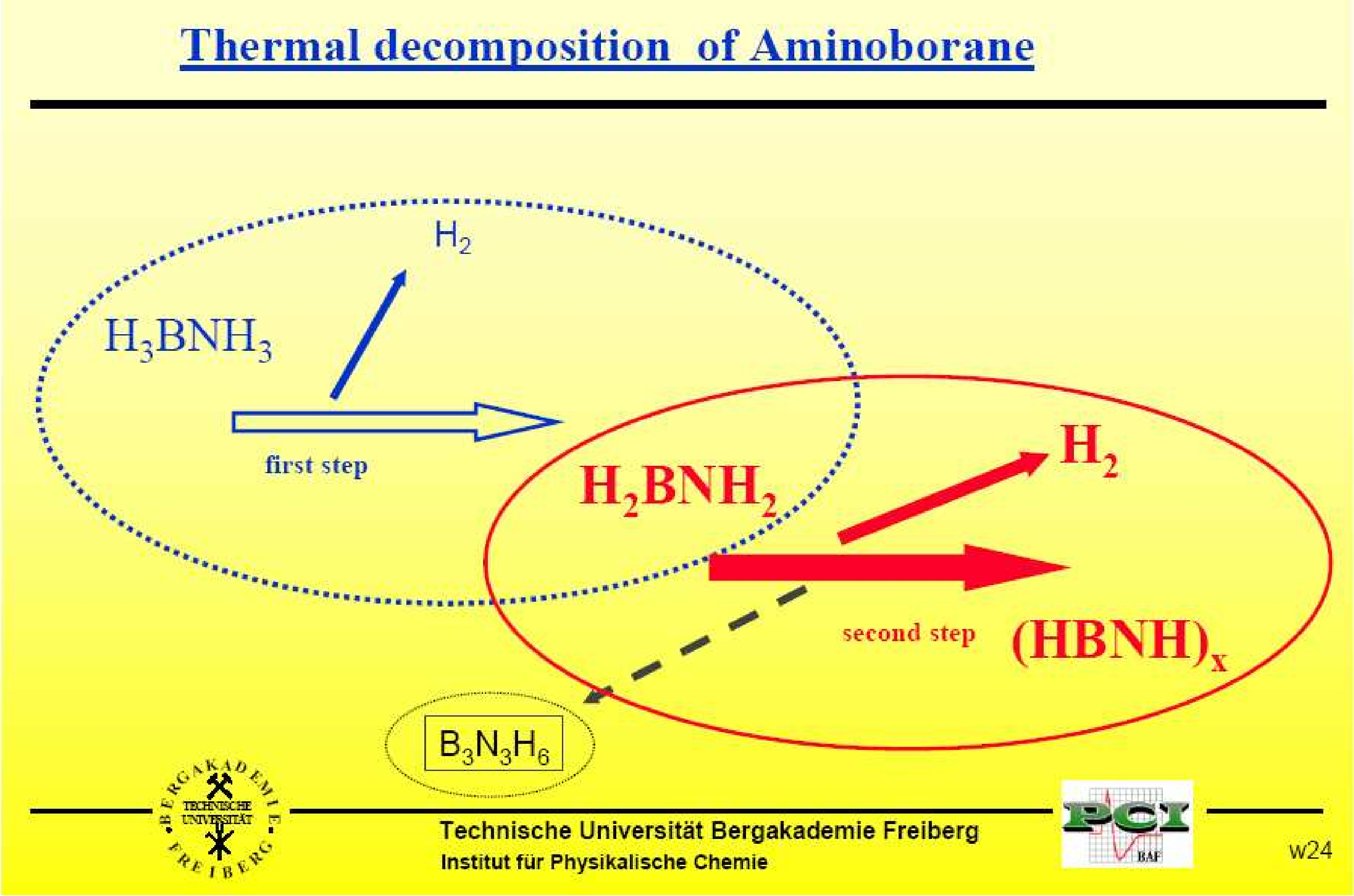
Thermal decomposition of BNH-compound



Thermal decomposition of Aminoborane

H_2

H_3BNH_3

first step

H_2BNH_2

H_2

second step

$(HBNH)_x$

$B_3N_3H_6$

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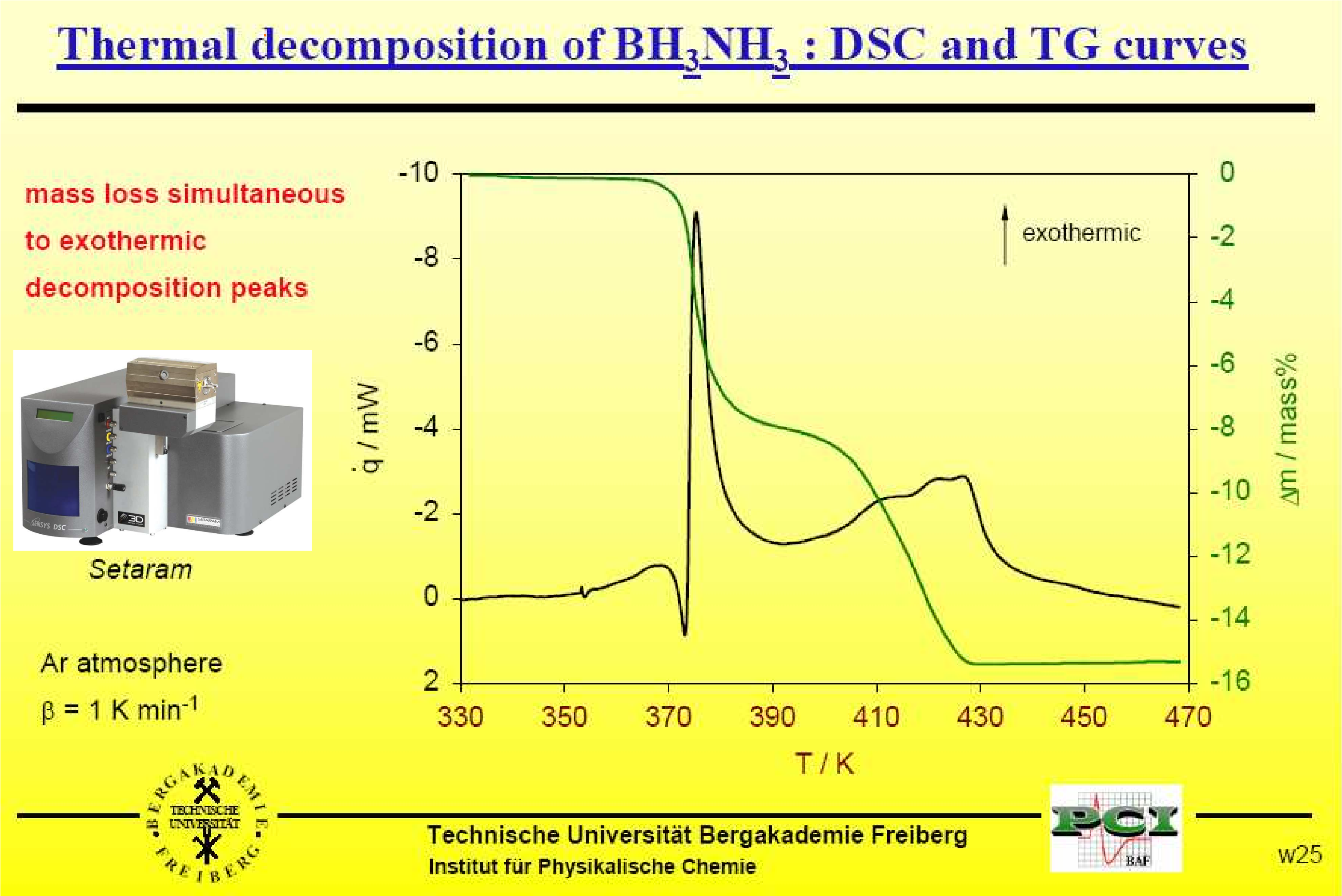
w24

Thermal decomposition of BNH-compound



Thermal decomposition of BH_3NH_3 : DSC and TG curves

mass loss simultaneous
to exothermic
decomposition peaks

Setaram

Ar atmosphere
$\beta = 1\ \mathrm{K\ min^{-1}}$

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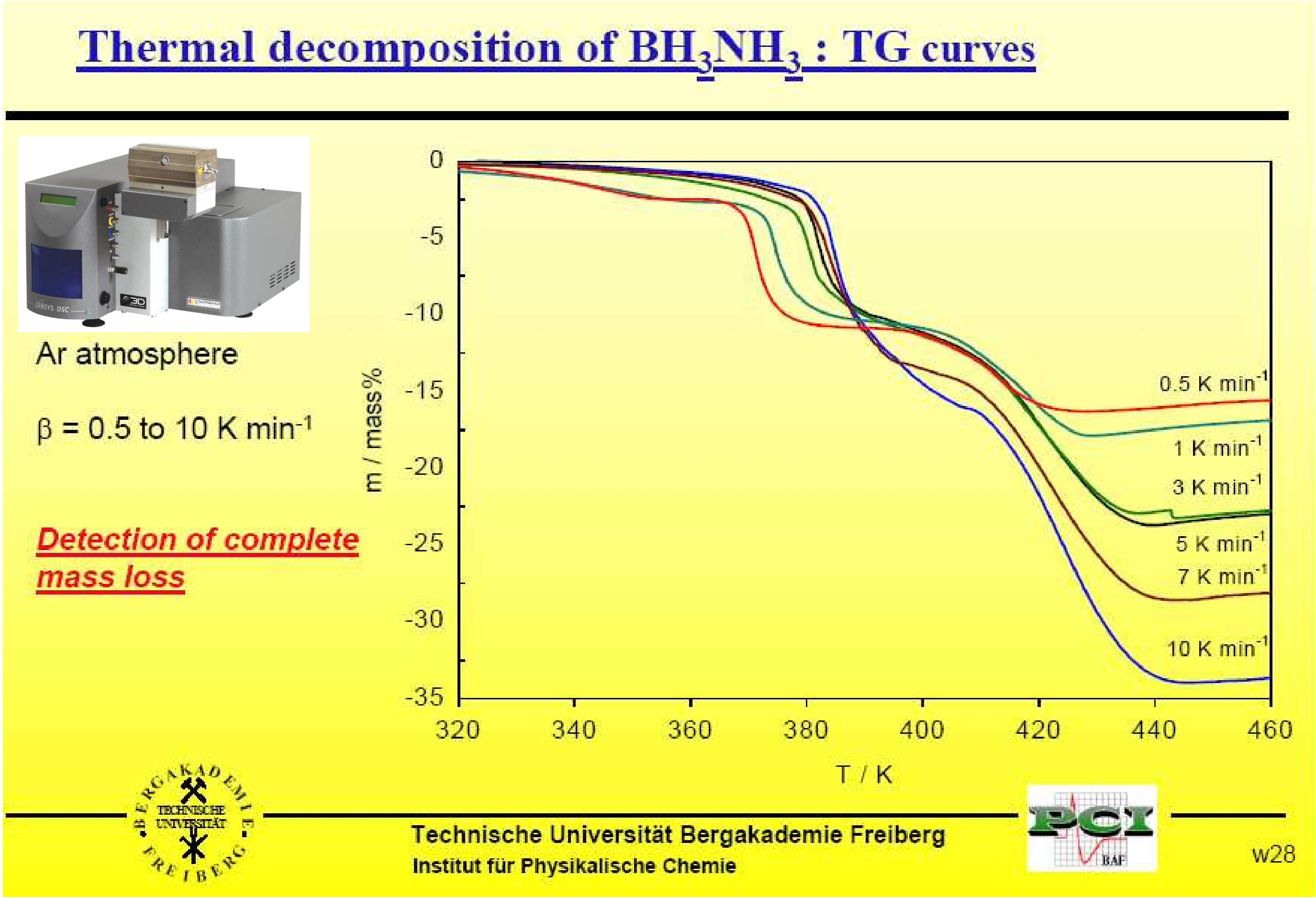
w25

Thermal decomposition of BNH-compound



Thermal decomposition of BH_3NH_3 : TG curves

Ar atmosphere

β = 0.5 to 10 K min^{-1}

Detection of complete mass loss

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Source of Information

SETARAM
Instrumentation
KEP Technologies

European projects

- HyChain (Air Liquide) in transportation
- StorHy in storage
- GECOPAC for SOFC fuel cell
- REAL-SOFC for SOFC fuel cell
- GREEN-FUEL-CELL for biomass conversion

Some actors in the Hydrogen market

- Europe
  - Axa ne (France) from Air Liquide
  - CEA (France) with Genepac
  - Helion (France) from Areva
  - Hydrocell Oy (Finland)
  - Intelligent Energy (UK)
  - Rolls Royce (UK)
  - Nuvera (Italy)
  - Siemens (Germany)
  - Vaillant (Germany)
- USA
  - APCa
  - Plug Power
  - UTC Power
  - FuelCell Energy
- Canada
  - Hydrogenics
  - Ballard
- Japan
  - Fuji Electric
  - Toshiba
  - Sanyo Electric
  - Matsushita Electrical Industrial
  - Mitsubishi
  - Sony

Shell Hydrogen
BP Solar

Some laboratories

- **Laboratories and research institutes**

Argonne National Laboratory (USA)
Brazilian Reference Center for Hydrogen Energy (Brésil)
Centre for Energy Research, SPIC Science Foundation (Inde)
CEA (France)
CIDETEC (Espagne)
ECN (Energy research Centre of the Netherlands)
Forschungszentrum Jülich (Allemagne)
Fuel Cell and Hydrogen Research Centre (Allemagne)
Georgetown University (USA)
Houston Advanced Research Center's (USA)
Hydrogen Research Institute (Canada)
Jet Propulsion Laboratory, NASA (USA)
National Fuel Cell Research Center (USA)
National Renewable Energy Laboratory (USA)
Risoe National Laboratory (Danemark)
Tongji University (Chine)
ZSW (Zentrum für Solarenergie- und Wasserstoff-Forschung) (Allemagne)
ZBT (Zentrum für Brennstoffzellentechnik) (Allemagne)

Some organisations

- DOE Hydrogen site
- DOE Renewable energy
- European Hydrogen Association
- Association française de l’Hydrogène
- The European Thematic Network on Hydrogen

Some useful sites

- http://www.cea.fr/fr/pedagogie/Hydrogene/Production.html
- http://www.enpc.fr/fr/formations/ecole_virt/trav-eleves/cc/cc0304/hydrogene/H2.htm
- http://www.annso.freesurf.fr/bases.html
- http://www.axane.fr/axane/fr/hydrogene_web/sites.cfm
- Fuel cell market

Search

- « Hydrogen storage » 3262 articles
- « Hydrogen storage calorimetry » 76 articles
- « Hydrogen storage DSC » 59 articles
- « Hydrogen storage thermogravimetry » 19 articles
- « Metal hydrides » 3544 articles
- « Fuel cell » 9436 articles

Hydrogen Companies

Companies

Generation

Air Products and Chemicals, Inc. (Allentown, PA)
Avalence LLC (Milford, CT)
BC Hydro (Burnaby, BC, Canada)
Canadian Hydrogen Association (Toronto, ON, Canada)
FuelMaker Corporation (Toronto, ON, Canada)
General Hydrogen (Calgary, AB, Canada)
Genesis Fueltech Inc. (Spokane, WA)
H2Gen Innovations, Inc. (Alexandria, VA)
HyRadix, Inc. (Des Plaines, IL)
MesoFuel, Inc. (Albuquerque, NM)
Millennium Cell, Inc. (Eatontown, NJ)
National Hydrogen Association (Washington, DC)
Praxair, Inc. (Danbury, CT)
PowerNova Technologies Corporation (Vancouver, BC, Canada)
Proton Energy Systems (Wallingford, CT)
QuestAir Technologies, Inc. (Burnaby, BC, Canada)
Shell Hydrogen (Amsterdam, The Netherlands)
Stuart Energy Systems Corporation (Mississauga, ON, Canada)
Sud-Chemie, Inc. (Louisville, KY)
Teledyne Energy Systems, Inc. (Hunt Valley, MD)
Ztek Corporation (Woburn, MA)

Storage

Dynetek Industries, Ltd. (Calgary, AB, Canada)
HERA Hydrogen Storage Systems, Inc. (Longueuil, QC, Canada)
QUANTUM Technologies, Inc. (Irvine, CA)

Fuel cells Developers (1)

Acumentrics Corporation, Massachusetts, USA (SOFC)
Advanced Measurements Inc., Alberta, CANADA (Fuel Cell Testing Systems)
Anuvu Incorporated, California, USA (PEM)
Apollo Energy Systems, Inc., Florida, USA (AFC)
Arbin Instruments, Texas, USA (Fuel Cell Testing Systems)
Argonne National Laboratory, Illinois, USA (PEM, MCFC and SOFC)
Asia Pacific Fuel Cell Technologies, California, USA (PEM, Hydrogen Storage)
Astris Energi, Inc., Mississauga, Ontario, CANADA (AFC)
Azienda Energetica Municipale (AEM spa Milano), Milano, ITALY (PAFC)
Ball Aerospace & Technologies Corp., Colorado, USA
Ballard Power Systems, Inc., British Columbia, CANADA (PEM)
BCS Technology, Inc., Texas, USA (PEM)
Case Western Reserve University, Ernest B. Yeager Center, Ohio, USA (PEM)
Celanese AG - Frankfurt, GERMANY (High Temperature MEAs)
Celsius, Malmo, SWEDEN (PEM)
Ceramatec, Utah, USA (SOFC)
Ceramic Fuel Cells Ltd., Victoria, AUSTRALIA (SOFC)
CMR Fuel Cells Limited, Cambridge, UK (DMFC)
Consejo Superior de Investigaciones Cientificas, Madrid, SPAIN (PEM, MCFC, SOFC)
CoorsTek, Colorado, USA (Ceramic fuel cell components)
Coval H2 Partners, California, USA (PEM)
CSIRO Energy Technology, New South Wales, AUSTRALIA
DAIS Corporation, Florida, USA (PEM)
DE NORA s.p.a., ITALY (PEM)
Desert Research Institute, Nevada, USA (PEM, PAFC)
Draeger Safety, Colorado, USA (PEM)
EBARA Ballard Corporation, Tokyo, JAPAN (PEM)
EBZ - Dresden, GERMANY (SOFC)
Electric Power Research Institute, California, USA (PAFC and MCFC)
Electrocell - Sao Paulo, BRAZIL
Electro-Chem-Technic, Oxford, UNITED KINGDOM (PEM, PAFC)
ElectroChem, Inc., Massachusetts, USA (PEM)
Element 1 Power Systems Inc., California, USA
Elf Atochem North America, Pennsylvania, USA (PEM)

Fuel cells Developers (2)

Emprise Corporation, Georgia, USA
Energia Ltd., Virginia, USA
EnergyOr Technologies Inc., Quebec, CANADA (PEM)
Energy Conversion Devices, Inc., Michigan, USA (RFC)
Energy Visions Inc., Ottowa, Ontario, CANADA (DMFC)
Esoro AG, Faellanden, SWITZERLAND (PEM)

ETH Materials, Zurich, SWITZERLAND (SOFC)
eVionyx, New York, USA (Metal-Air FC)
Federal Energy Technology Center, West Virginia, USA (MCFC and SOFC)
FEV Motorentechnik GmbH, GERMANY (PEM, SOFC)
Florida Solar Energy Center, Florida, USA (PEM)
Forschungszentrum Julich, GERMANY (DMFC, SOFC & PEM)
FuelCell Energy, Connecticut, USA (DFC)
Fuel Cell Resources Inc. - Georgia, USA (PEM membranes)
Fuel Cell Systems - West Sussex, UNITED KINGDOM (AFC)
Fuel Cell Technologies, Ltd., Ontario, CANADA
Gas Technology Institute, Illinois, USA (MCFC, PAFC, , PEM and SOFC)
Gaskatel GmbH, Kassel, GERMANY (AFC & PEM)
Gaz De France, La Plaine, FRANCE (PAFC, PEMFC, SOFC)
GE Energy and Environmental Research Corp., California, USA (PEM, MCFC, SOFC)
GreenVolt Power Corporation, CANADA (AFC)
Hitachi Works, Ibaraki, JAPAN (MCFC)
Hoku Scientific, Hawaii, USA (PEM)
HTceramix - Lausanne, SWITZERLAND (SOFC)
H-Tec - Wasserstoff-Energie-Systeme GmbH, Luebeck, GERMANY (PEM)
Hydro Quebec Research Institute, Quebec, CANADA
Hydrocell U.K., UNITED KINGDOM (AFC, PEM)
Hydrogenics Corporation, Toronto, CANADA
Hydrovolt Energy Systems, California, USA (SOFC)
ICP-CSIC, Madrid, SPAIN
ICTP-CSIC, Madrid, SPAIN (PEM)
ICV-CSIC, Madrid, SPAIN (SOFC)
IdaTech, Oregon, USA (PEM)
InnovaTek, Inc., Washington, USA
Ion Power, Inc., Delaware, USA (PEM)

Fuel cells Developers (3)

Japan Automobile Research Institute, Inc., JAPAN (PEM)
JLG Industries, Pennsylvania, USA (PEM)
Korea Institute of Science and Technology, KOREA (PEM, MCFC, SOFC, DMFC, DFAFC (direct formic acid)
Lawrence Berkeley Laboratory, California, USA (PEM)
Lawrence Livermore National Laboratory, California, USA
Los Alamos National Laboratory, New Mexico, USA (PEM)
Lund Institute of Technology, Lund, SWEDEN (SOFC)
Lynntech, Inc., Texas, USA (PEM)
Manhattan Scientifics Inc., New Mexico, USA (PEM)
Massachusetts Institute of Technology, Massachusetts, USA (PEM, SOFC)
Materials and Electrochemical Research Corporation, Arizona, USA (PEM)
Materials and Systems Research, Inc., Utah, USA (SOFC)
McDermott Technology, Inc., Ohio, USA (PEM, SOFC)
Medis Technologies, ISRAEL (PEM)
Metallic Power, California, USA (ZFC)
Microcell, North Carolina, USA (PEM)
Mitsubishi Electric Corporation, JAPAN (PAFC)
Mitsubishi Heavy Industries, Inc., New York, USA (PEM & SOFC)
MTU Friedrichshafen GmbH, GERMANY (MCFC)
National Aeronautics and Space Administration, Ohio, USA (regenerative FCs)
National Aerospace Laboratory, JAPAN (PEM)
National Fuel Cell Research Center, California, USA
National Renewable Energy Lab, Colorado, USA (PEM)
Netherlands Energy Research Foundation, NETHERLANDS (PEM, MCFC and SOFC)
NexTech Materials, Ltd., Ohio, USA (PEM & SOFC)
NuVant Systems, Inc., Illinois, USA (PEM, DMFC)
OMG Corp., Michigan, USA (PEM)
Ontario Hydro Technologies, Ontario, CANADA (SOFC)
Pacific Northwest National Laboratory, Washington, USA (PAFC, MCFC and SOFC)
Pivotal Power, Nova Scotia, CANADA (Fuel Cell Components)
Plug Power, LLC, New York, USA (PEM)
Powerzinc Electric, Inc., CA, USA (Zinc/Air)
Protonex Technology Corporation, Massachusetts, USA (PEM)
Proton Energy Systems, Connecticut, USA (PEM, Regenerative)
Proton Motor GmbH - Starnburg, GERMANY (PEM)
Refrac Systems, Arizona, USA
ReliOn, Washington, USA (PEM)
Risø National Laboratory, Roskilde, DENMARK (SOFC)
Rocky Mountain Institute, Colorado, USA (PEM)

Fuel cells Developers (4)

Sandia National Labs, New Mexico, USA
Schafer Corporation, California, USA (PEM)
Schatz Energy Research Center (SERC), California, USA (PEM)
Siemens Westinghouse Power Corporation, Pennsylvania, USA (SOFC)
South Coast Air Quality Management District, California, USA (PAFC, PEM)
Southeastern Technology Center, Georgia, USA (PEM)
Southern States Power Co., Louisiana, USA (PEM)
Southwest Research Institute, Texas, USA (PEM)
Sulzer Hexis Ltd., SWITZERLAND (SOFC)
TATA Energy and Resources Institute (TERI), INDIA (MCFC)
Technology Management, Inc. (TMI Systems), Ohio, USA (SOFC)
Teledyne Energy Systems, Inc., Maryland, USA (Fuel cell testing, PEM, Hydrogen generation)
TNO Energy & Environment, Apeldoorn, NETHERLANDS (PEM)
Toshiba Corporation, Yokohama, JAPAN (PAFC and PEM)
Toyota Motor Corporation, JAPAN (PEM)
United States Department of Energy (main), Washington D.C., USA (PAFC, PEM, MCFC and SOFC)
United States Department of Energy (Office of Hydrogen, Fuel Cells & Infrastructure Technologies), Washington D.C., USA (ALL)
United Technologies Research Center (UTRC), Connecticut, USA (PAFC and PEM)
UTC Power, Connecticut, USA (PAFC and PEM)
Voller Energy, Hampshire, United Kingdom (PEM)
VTT Chemical Technology, FINLAND (PEM)
Warsitz Enterprises, California, USA (PEM)
Westinghouse Savannah River Company, Georgia, USA (PEM, SOFC)
Worcester Polytechnic Institute, Massachusetts, USA (PEM)
ZSW, Center for Solar Energy & Hydrogen Research, Ulm, GERMANY (PEM, MCFC and SOFC)
Ztek Corporation, Massachusetts, USA (SOFC and Hydrogen Reformers)