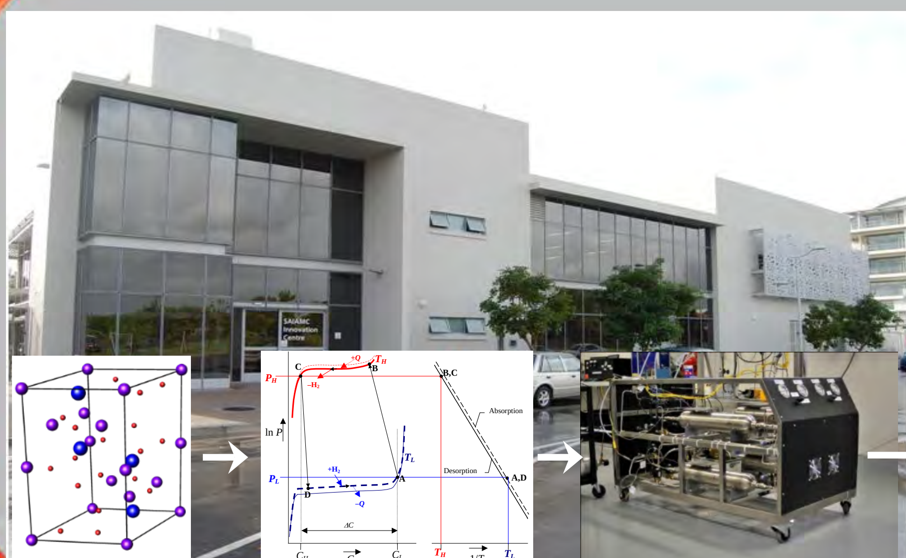
M.Lototskyy

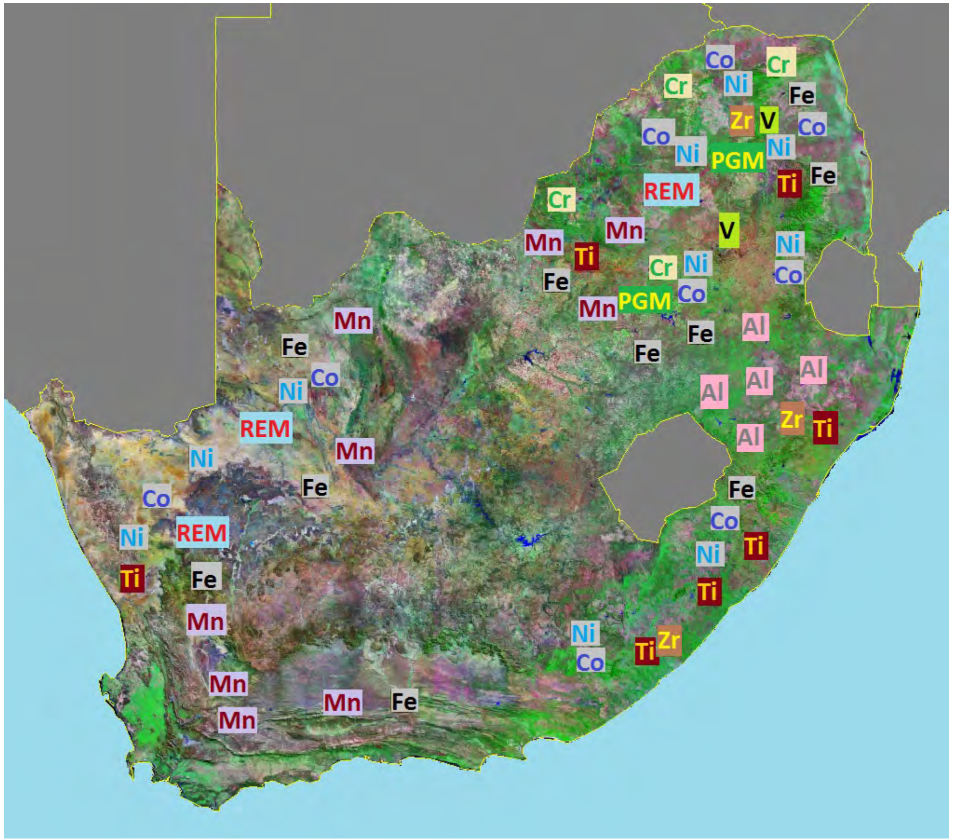
Metal Hydrides – from Basic Materials Development to Applications

Overview of MH-related R&D activities of SAIAMC / HySA Systems MH team



Hydrogen South Africa (HySA): Motivation

Product	Reserves		Applications
	% of world total	Rank	
Platinum Group Metals (PGM)	>75%	1	Hydrogen & Fuel Cell Technologies
Rare-Earths	0.7%	9	Metal Hydride Materials & Technologies
Titanium	7.9%	4	
Zirconium	18.9%	2	
Manganese	29.4%	1	
Chromium	39.2%	2	
Vanadium	17.5%	3	
Nickel	5.0%	7	



Hydrogen South Africa (HySA): Organization

HySA Hydrogen South Africa

DST

- HySA Infrastructure – Hydrogen South Africa: NWU / CSIR
- HySA Catalysis – Hydrogen South Africa: UCT / Mintek
- HySA Systems – Hydrogen South Africa: UWC

HysA Systems: What we do

Department of Science & Technology

HySA Systems

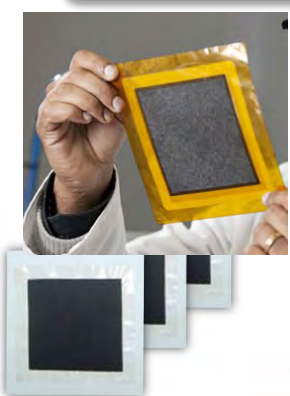
Combined Heat & Power

- HT-MEA
- System Integration
- System Validation
- System/Stack Modelling

Hydrogen Fuelled Vehicles

- HT -MEA
- HT-PEMFC Stacks
- System Integration
- System Validation
- System/Stack Modelling

Key Technologies



- ✓ High Temperature PEM Fuel Cell Stacks (>120˚C)
- ✓ HT-MEAs for HT-PEMFCs
- ✓ Solid State Hydrogen Storage (MH)
- ✓ Li-ion Batteries
- ✓ Pd-membranes
- ✓ Power Modules for Hybrid Hydrogen Fuel Cell Vehicles

HySA Systems: resources

Total 3000 m^2 usable floor space

- 250 m^2 testing of fuel cell systems
- 150 m^2 MEA processing and fuel cell preparation
- 1000 m^2 of MH pilot plant

Total 38 (7) people:
Director, 2 Programme Managers, 3 Key technology specialists, 3(1) engineers
10(2) post-doctoral, 5(1) PhD and (4)MSc students
3(1) technicians and 2 research assistants
1 administrative staff, 6 Support Staff

HySA Systems Hydrogen South Africa

SAIAMC South African Institute for Advanced Materials Chemistry MAKING RESEARCH WORK

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MH activities at SAIAMC and HySA SYSTEMS

Background

- Strong expertise in synthetic procedures:
  - Melting & annealling
  - Surface modification / electroless plating (PGM)
  - Carbon nanomaterials (CNT)
  - Reactive Ball Milling

- Various analytical facilities + necessary skill
  - XRD, SEM, TEM
  - BET, DSC
  - Gas analysis (GC, MS)
  - Sieverts apparatus
- Computer modelling (PCT, kinetics, heat-and-mass transfer)

- Infrastructure + necessary skill for components & systems manufacturing and testing
- Strong international links with MH and HFCT teams (Norway, Germany, Croatia, China, Russia, etc.: both MH materials and systems)

MH activities at SAIAMC started in 2004

Recently Completed and Actual MH Related Activities at SAIAMC and HySA Systems

- Poisoning-tolerant surface modified MH materials. MH systems for H_2 separation & purification
- AB_5- and AB_2-type MH alloys: preparation (up to 15 kg/load) & characterisation
- Mg-based nanocomposites for H storage and heat management
- Thermally-driven MH H_2 compressors
- MH system integration:
  - H storage systems for LT PEM FC applications
  - H storage (+ refuelling) systems for utility vehicles




Funding Sources

- South African Government *(incl. co-funding of international collaborative projects)*:
  - Department of Science and Technology (DST);
  - National Research Foundation (NRF);
  - Department of Trade and Industry (DTI) via THRIP programme.
- South African industry:
  - Eskom Holdings Limited;
  - Impala Platinum.
- International funding:
  - EU via H2020 / RISE program.

Total budget of MH-related projects at SAIAMC – ~ R5m / y

MH projects (HySA funded)

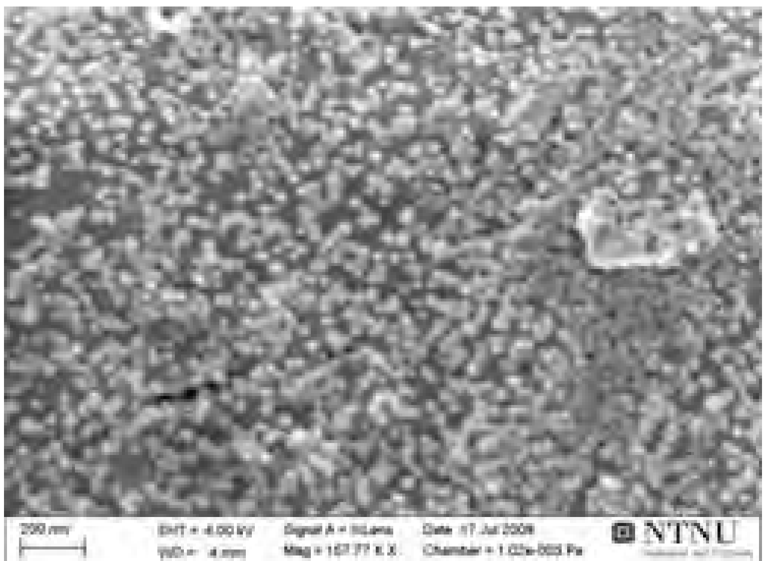
- Key Programme 2 – Portable Power Systems:
  - KP2-S01 – MH H2-Storage for LT PEMFC Power Systems (2008–2010).
- Key Programme 3 – Hydrogen Fuelled Vehicles:
  - KP3-S02 – On Board Use of Metal Hydrides for Utility Vehicles (2008–present);
  - KP3-S04 – On-Board Hydrogen Storage (2008–2012).
- Key Programme 8 – Special Projects:
  - KP8-S02 – Metal Hydride Integrated Energy Systems (2008–2011);
  - KP8-S05 – Metal Hydrides for underground Mining Applications (2015–present).

HySA Systems projects (Additional funding)

- **South African Government:**
  - DST Innovation Project – South African Metal Hydride Alloys: Proof of Concept (2012–2014);
  - DTI / NRF THRIP project – Advanced Materials and Technologies for Hydrogen-Powered Utility Vehicles (2013–2015).
- **South African industry:**
  - Eskom – Materials and Processes for UCG product gas, clean up and storage (MH materials and systems for hydrogen separation, purification and compression; 2008–2015);
  - Impala Platinum – Development of a Fuel Cell Powered Forklift Utilising Advanced Metal Hydride Hydrogen Storage and Refuelling (2012–present);
  - Anglo American Platinum – Underground use of FC Technologies (2014–2015).
- **International funding:**
  - International Science and Technology Agreements South Africa – Norway – Industrial Applications of Metal Hydrides for Hydrogen Extraction, Storage and Compression / HYDROTECH (co-funded by NRF, 2007–2010, prolonged to 2013);
  - ERAfrica FP7 Programme – Advanced Hydrogen Energy Systems / HENERGY (co-funded by DST, 2014–2018);
  - Horizon 2020 / RISE Programme – Hydrogen fuelled utility vehicles and their support systems utilising metal hydrides / HYDRIDE4MOBILITY (started in February 2018).

Poisoning-Tolerant Surface Modified MH Materials

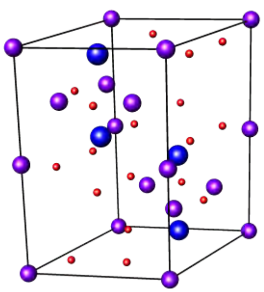
- **2007-2012; completed:**
  - ESKOM-funded SAIAMC project;
  - South Africa – Norway Research collaboration project;
  - HySA Systems project KP8-S01.

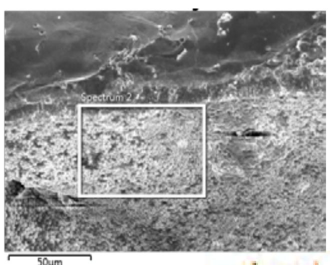


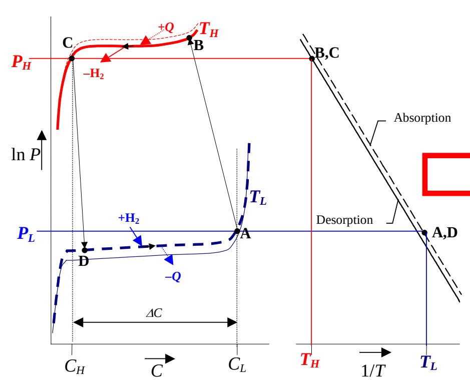
- Substrate: AB_5 (A=La; B=Ni+Co+Mn+Al
- Surface modification: fluorination + functionalisation + electroless deposition of Pd (2 international patents)
- No significant deterioration of the surface modified MH was observed (CO up to 100 ppm, CO_2 up to 30%)
- Introduction of CO_2 + CO reduces H_2 separation productivity by 20% only, stable performance over ~200 cycles.

AB_5- and AB_2-type MH alloys for H storage & compression

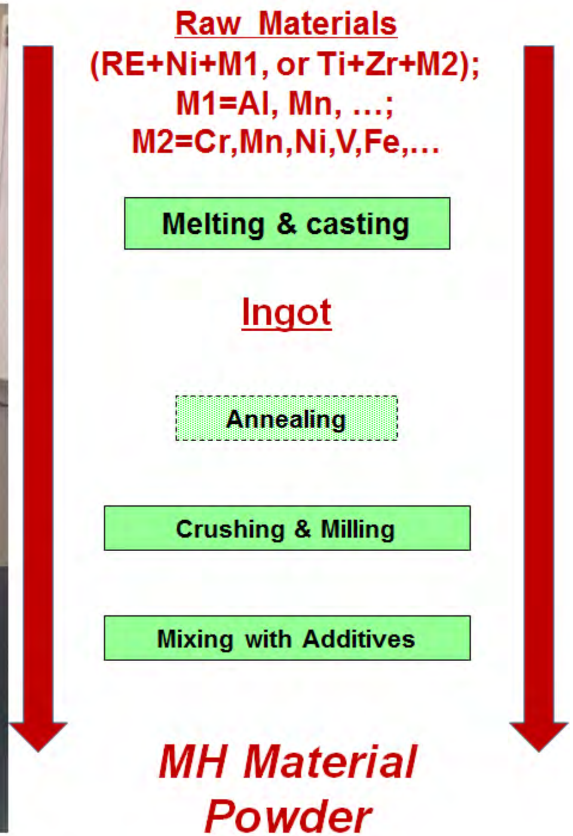
- **2009 – …; on going:**
  - DST innovation project;
  - HySA Systems projects KP3-S02, (KP8-S01), KP8-S05.







MH Alloys Manufactured at HySA Systems



- Locally developed induction melting and annealing furnaces
- Production capacity up to 15Kg per a load
- Original recipes (AB_5 & AB_2): *customized compositions according to customer's specifications, including target PCT performances for H_2 absorption / desorption*
- Mostly South African feedstock
- H storage capacities 160 to ≥200 Ncm^3/g
- H_2 equilibrium pressures at T=20°C from <1 to ~50 bar
- Suitable for H storage and H_2 compression applications
- Patented solution on the preparation of MH composite and its loading in MH container: *easy activation, tolerance to gas impurities, low pyrophority, and better heat transfer performances of the MH bed*.

The MH manufacturing facilities were built due to SA Government (DST) funding

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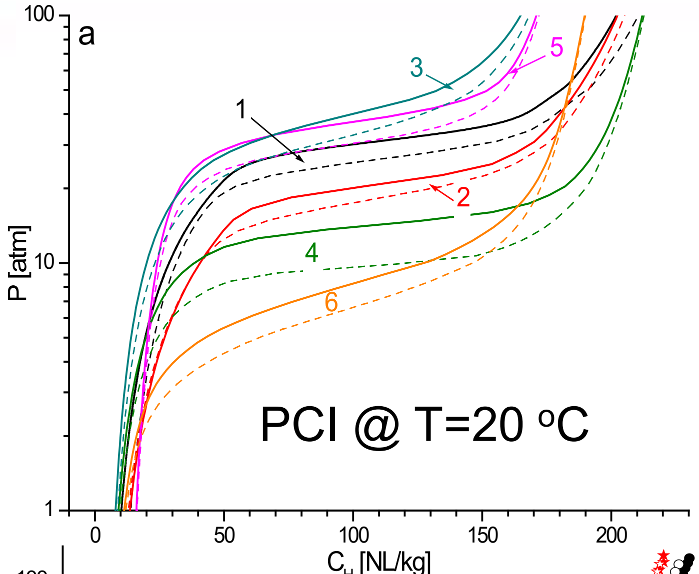
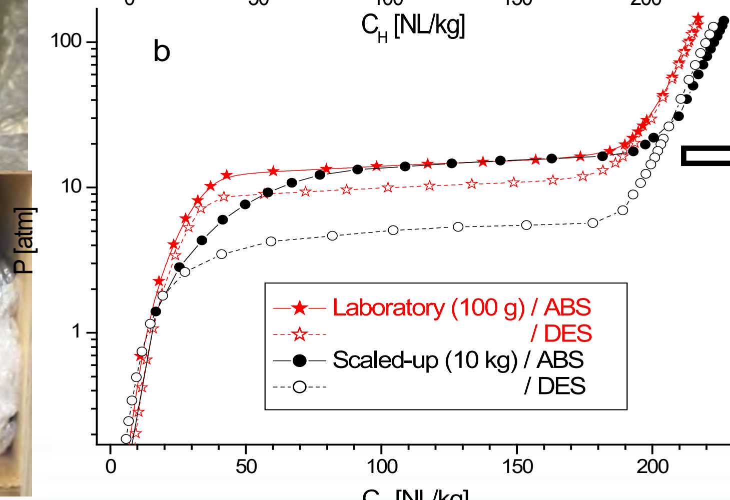
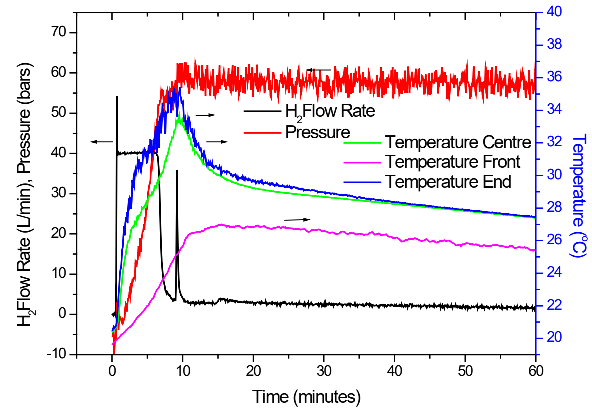
Some AB_2-type MH materials manufactured at HySA Systems

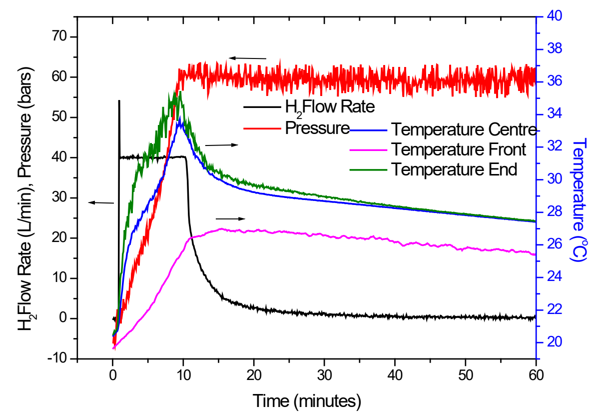




H_2 absorption tests in MH tank



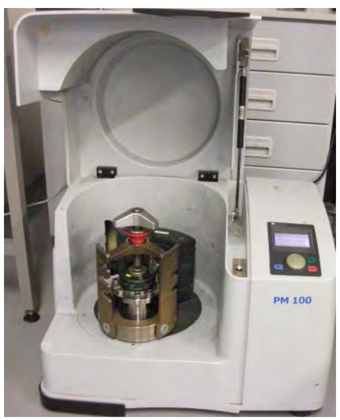
Imported AB_2: 3.1 kg / **503 NL H_2**

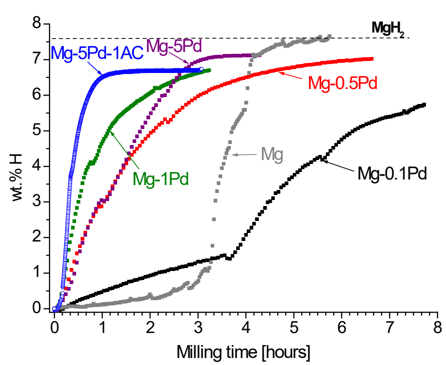


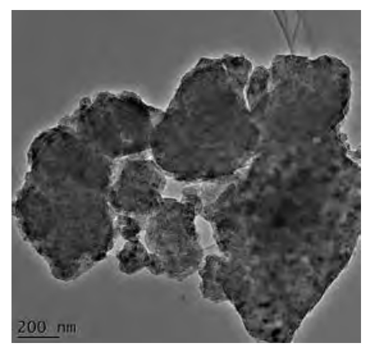
In-house produced AB_2: 2.9 kg / **624 NL H_2**

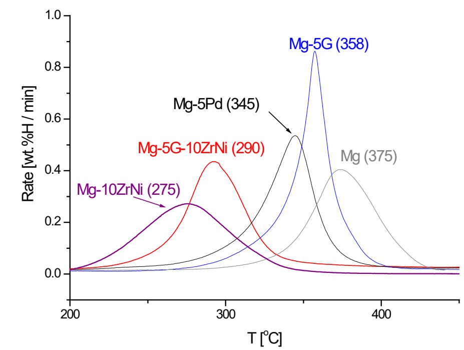
Mg-based nanocomposites for H storage and heat management

- **2007 – …; on going:**
  - South Africa – Norway research collaboration project;
  - EU FP7 “ERAfrica” research collaboration project (NO, TR, EG, ZA);
  - HySA Systems projects KP3-S02, (KP3-S04);
  - THRIP project.









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ERAfrica new knowledge partnerships

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NRF

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Thermally-driven MH H_2 compressors

- **2008-…; on-going:**
  - ESKOM-funded SAIAMC project;
  - HySA Systems projects KP3-S02, (KP8-S01).




Objective / general approach

- To develop prototype MH H_2 compressors potentially satisfying the requirements of industrial consumers:
  - Providing necessary H_2 pressure (up to 200 bar) and productivity (x 1…10 m^3/h);
  - Operation using available infrastructure for heating (steam, water; up to 150 ^oC) and cooling (water; 15…25 ^oC);
  - Competitive cost / performance / service requirements as compared to available prototypes.

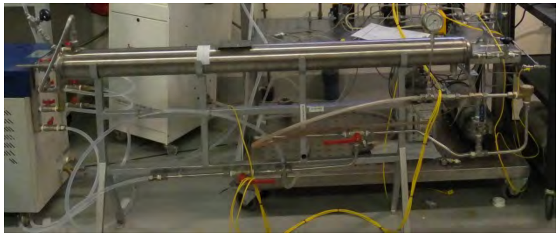
MH containers for H_2 compression

A. Small-scale

- 4x ½" OD SS tubes in heat-distributing Al block
- 10 (2 stages) to 20 (1 stage) NL H_2
- Electric heating, water cooling
- Heating / cooling time 5-10 min

B. Medium-scale

- Internal HE with fins
- Up to 2 Nm^3 H_2
- Steam (or pressurised water) heating, water cooling
- Heating / cooling time ~35-40 min
- Fully certified according to SA regulations (200 bar @ 200 ^oC)



C. Industrial-scale

- Extruded internal HE with fins + external heating / cooling jacket
- 2.5 Nm^3 H_2
- Steam heating, water cooling
- Heating / cooling time ~20-25 min
- Fully certified according to SA regulations (200 bar @ 200 ^oC)

MH H_2 compressors developed at SAIAMC

Eskom

2008: Small-scale prototype
- 2 stage layout (1 – AB_5; 2 – AB_2)
- Electric heating (130 °C), water cooling (15..25°C)
- H_2 compression in the range 7 – 200 bar
- Productivity up to 60 NL/h

2011: Medium-scale prototype
- 2 stage layout (1 – AB_5; 2 – AB_2)
- Steam / pressurised water heating (130 °C), water cooling (15..25°C)
- H_2 compression in the range 10 – 200 bar
- Productivity up to 1 Nm^3/h

2014: Industrial-scale prototype
- 3 stage layout (1,2 – AB_5; 3 – AB_2)
- Steam heating (140 °C), water cooling (15..25°C)
- H_2 compression in the range 3 – 200 bar
- Productivity up to 5 Nm^3/h

Testing facilities (industrial scale MH compressors)

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Eskom MH Compressor Testing Facility

SAIAMC · Eskom

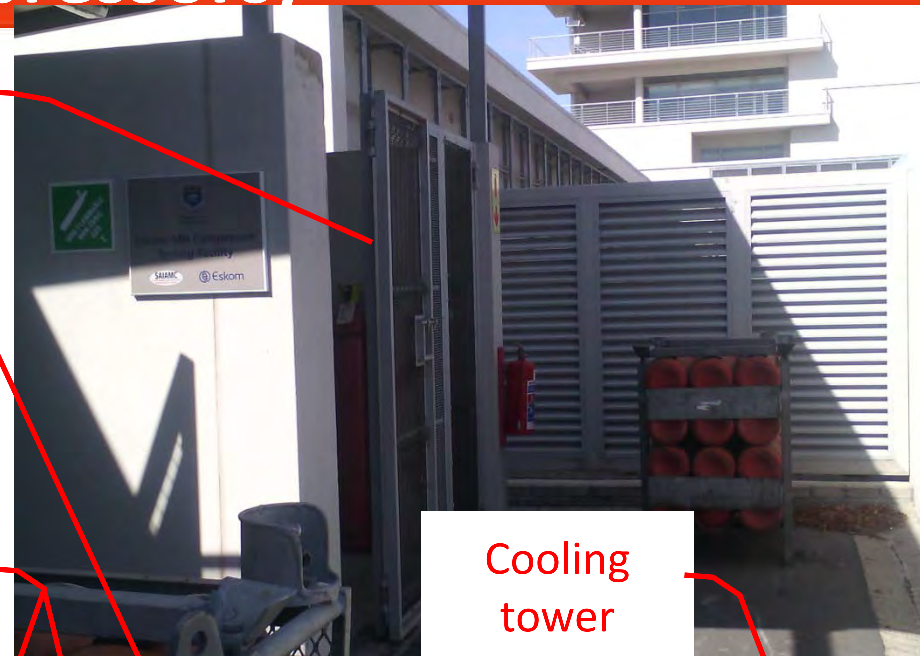
- Recently commissioned;
- Will be used to fill H_2 cylinders from electrolyser;
- On-going tests.

SAIAMC H_2 storage compartment

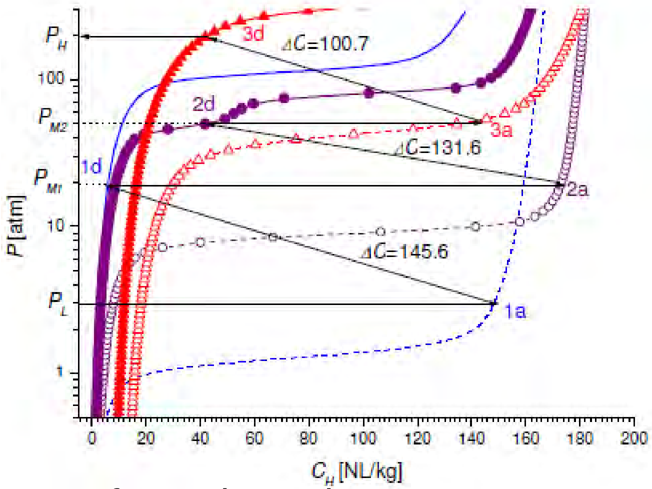
Steam generator

MH compressor

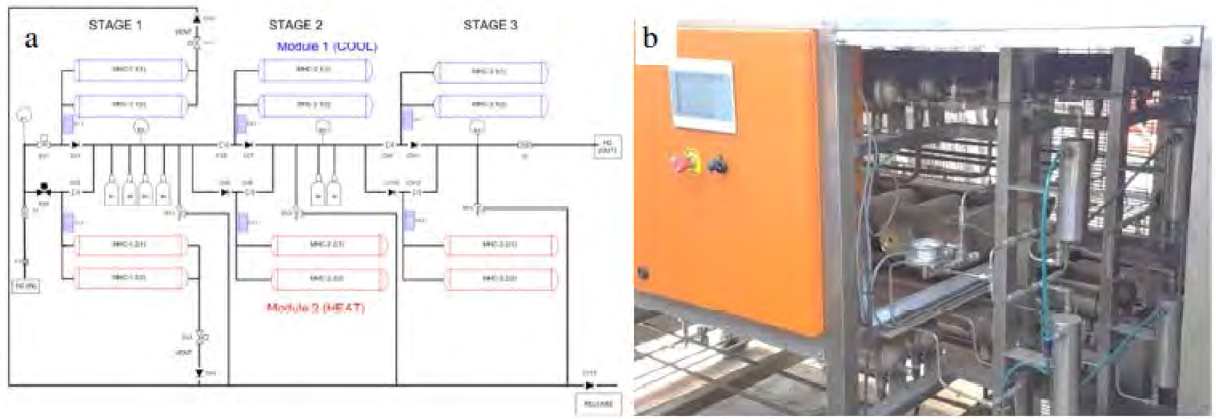
Cooling tower



Prototype 3-stage MH hydrogen compressor: test results

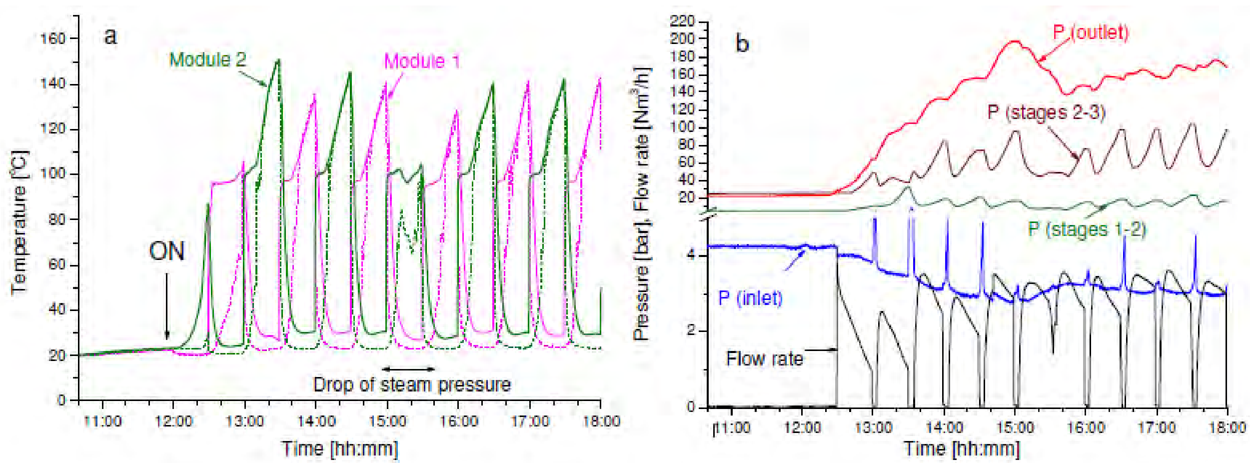


PCT for H absorption at T_L=298 K (a) and H desorption at T_H=403 K (d) for: $LaNi_{4.9}Sn_{0.1}$ (1), $La_{0.8}Ce_{0.2}Ni_5$ (2) and C14-$Ti_{0.65}Zr_{0.35}(Mn,Cr,Fe,Ni)_{2+x}$ (3).



Simplified gas piping diagram (a) and general view (b).

- 3 stage layout (1,2 – AB_5; 3 – AB_2)
- T_L ~20 °C (water), T_H ~130 °C (steam);
- P_L ≥3 bar, P_H ≤200 bar
- Productivity up to 5 Nm^3/h



Typical operation: (a) temperatures of the compression modules; (b) H_2 pressures and input flow rate.

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TFD THERMODYNAMICS FLUIDS & DESIGN
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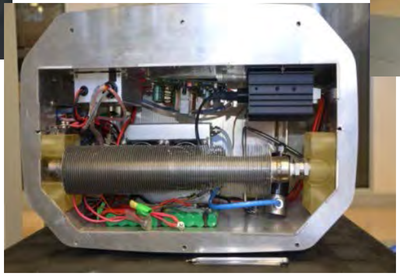
MH system integration

- **2011-…; on-going:**
  - HySA Systems projects KP3-S02, KP3-S03, KP8-S05;
  - Impala Platinum funded HySA Systems project;
  - THRIP project;
  - H2020 / RISE project



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IMPALA PLATINUM

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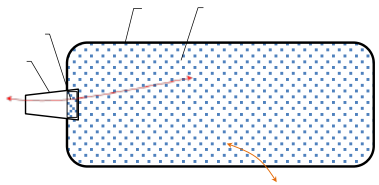
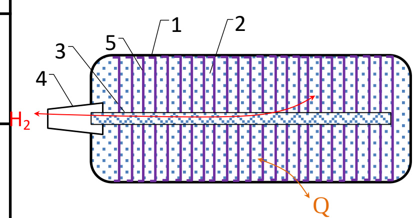
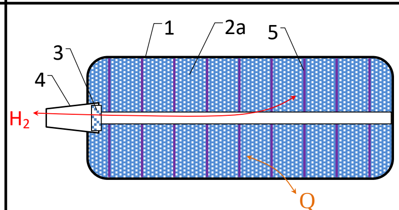
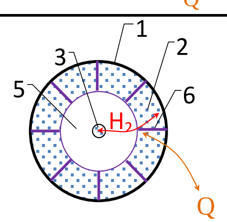
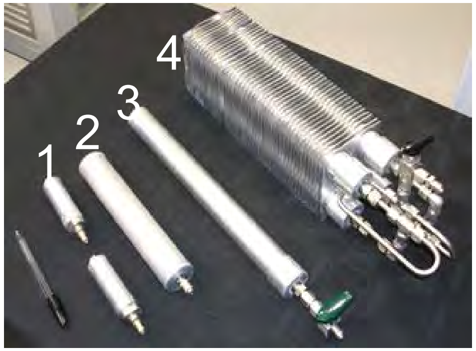
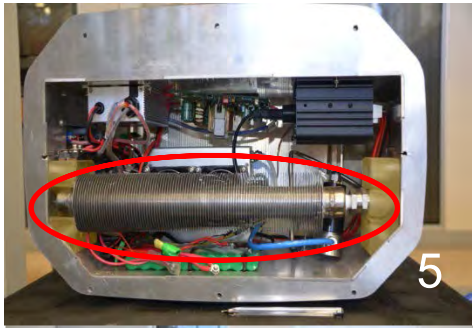
Metal hydride containers (1)

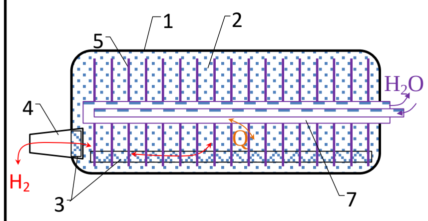
#	Inner layout	H storage capacity [NL]	Charge time [min]	Size [mm]	Weight: MH / Total [kg]
1		10.5	10	Ø25 x 100	0.07/0.16
2		90	45	Ø38 x 226	0.52/0.84
3		90	60	Ø34 x 330	0.60/1.01
4		360	50	100 x 100 x 360	2.40/4.52
5		90	15	Ø30 x 350	0.56/1.92
6		700	120	Ø110 x 800	5.3/21.3

- Air heated / cooled
- H storage for FC systems (10W to 1 kW)

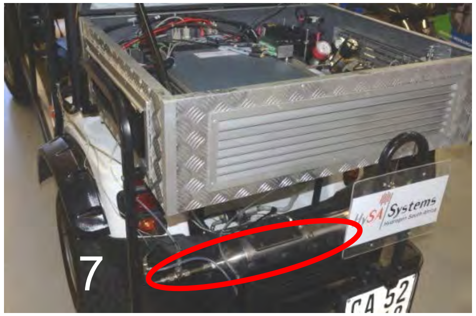




Metal hydride containers (2)

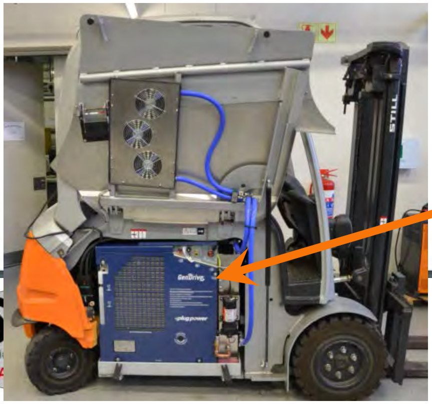
#	Inner layout	H storage capacity [Nm³]	Charge time [min]	Size [mm]	Weight: MH / Total [kg]
7		2	30-60	Ø115 x 1060	12.2/32.0
8	—H_2O →	0.5	10-15	Ø51.3 x 800	3.5/14.0
9		10	15	Ø34 x 330	70/250

- Liquid heated / cooled
- H storage for FC systems (1 to 15 kW)
- H_2 compression



1 – containment; 2 – MH powder, 2a – MH/TEG compacts; 3 – gas filter; 4 – gas connector; 5 – transversal fins; 6 – longitudinal fins; 7 – core of inner heat exchanger; H_2 – hydrogen flow; Q – heat supply / removal; H_2O – flow of heating / cooling water.

Layouts for ## 2-5, 8: *Patent application WO 2015/189758 A1*



9

MH for forklift: Project Highlights

- The objective of this project co-funded by Impala Platinum Ltd and the DST is to integrate metal hydride (MH) technologies for on-board hydrogen storage and related applications into utility vehicles providing their efficient system solutions, through the development of MH-based system components.
- The specific activities in the realising this objective included:
  - Integration of MH H storage and supply system in fuel cell powered forklift;
  - Development of the prototype forklift refuelling system with 50-200 bar 7-12 Nm^3/h MH compressor;
  - Start-up and field tests of the hardware at the site of industrial customer (Impala Platinum Refineries).

IMPLATS Distinctly Platinum

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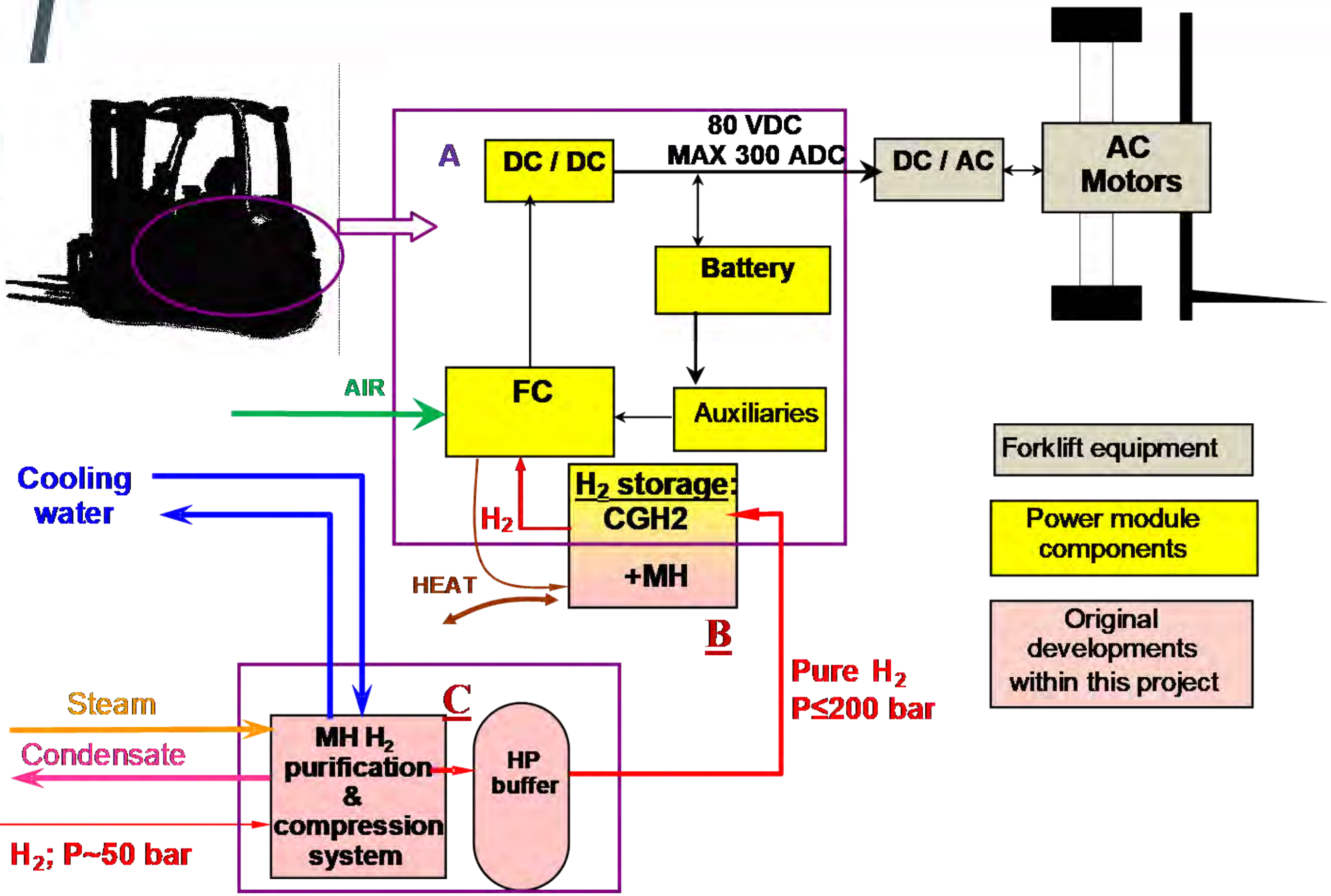
System Concept



- STILL RX-60-30 electric forklift, 3 ton lifting capacity, 80 VDC bus voltage.
- Commercial on-board fuel cell power module (**A**; GenDrive 1000 160X-80CEA / Plug Power) replacing the forklift battery and equipped with:
  - built-in CGH2 hydrogen storage system and
  - MH hydrogen storage extension tank (**B**).
- Stationary hydrogen refuelling system (**C**) consisting of a low-pressure H_2 supply and a MH hydrogen compressor.

More details to be given in HYDRIDE4MOBILITY overview presentation

Future plans

- MH materials:
  - Optimising compositions and manufacturing procedures of MH alloys for H_2 compression (AB_5 – ≤1 bar; AB_2 – >400 bar).
- Integrated systems:
  - Forklifts, mine locomotives (FC power modules with integrated MH storage);
  - Small-to-medium scale MH H storage and supply systems for various applications.
- MH H_2 compressors:
  - Lowering suction pressure to ≤1 bar while maintaining productivity x10 Nm^3/h;
  - Increase of discharge pressure to 400–700 bar (CGH2 refuelling systems).
- Other MH based systems:
  - Heat management applications;
  - …

Thank you for listening!

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www.hysasystems.com

Extra slides

HySA Strategic Goals

- Develop local cost competitive hydrogen generation solution based on renewable resources
- Wealth creation through value added manufacturing of PGM catalysis, goal- supply 25% of PGM catalysts demand by 2020
- Promote equity and inclusion in the economic benefits of South Africa's resources, SMEs to play an important role

science & technology
Department: Science and Technology
REPUBLIC OF SOUTH AFRICA

From: Dr Phil Mjwara, DG-DST: "Vision 2030: Hydrogen and Fuel Cells in SA", IPHE Meeting, Cape Town, 03 May 2012

HySA Implementation Plan

Technology catch-up	South African Extension	South African Innovation
2008 - 2013	**2013 - 2018**	**2018 - 2023**
• Key Personnel is hired • Research Infrastructure is set up • Initial markets are identified • First pre-commercial technologies developed	• Establish critical supply chain capability • Deliver first products to market • Demonstrate capabilities in pilot markets	• Contribute to international innovation • Compete successfully on world market • Capture 25% of Catalyst Demand in Hydrogen and Fuel Cells

HySA Systems: Academic Collaborations

Newcastle University

TU Graz — Graz University of Technology

ipen

同济大学 TONGJI UNIVERSITY

UPC — UNIVERSITAT POLITÈCNICA DE CATALUNYA

Indian Institute of Technology Delhi

IFE — Institute for Energy Technology

UNIVERSITY OF SPLIT — FACULTY OF ELECTRICAL ENGINEERING, MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE — FESB

Faculty of Engineering, Cairo University

ORTA DOĞU TEKNİK ÜNİVERSİTESİ — MIDDLE EAST TECHNICAL UNIVERSITY

Helmholtz-Zentrum Geesthacht — Zentrum für Material- und Küstenforschung

ИПХФ РАН

भारतीय प्रौद्योगिकी संस्थान गुवाहाटी — INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI

MH related projects:

- ✓ Completed: ZA–NO research collaboration program
- ✓ Ongoing: EU FP7 international collaboration project (NO, TR, ZA, EG; ERAfrica program) –PhD project co-supervised
  - ✓ Recently granted: Horison 2020 RISE project (NO, DE, HR, ZA, ID);
  - ✓ Submitted: BRICS project proposal (ZA, CN, RU, IN)

H_2 separation and purification using surface-modified MH materials: *patents* and main publications

- *M.Williams, M.V.Lototsky, A.N.Nechaev, V.M.Linkov. Method of surface modification of metallic hydride forming materials, WO 2009/066263 A1: Patents ZA2010/03334 US 8354552 B2*
- *M.Williams, M.V.Lototskyy, A.N.Nechaev, V.M.Linkov. Hydride-forming material, Patent ZA 2008/09123*
- M. Williams, C.A. Pineda-Vargas, E.V. Khataibe, B.J. Bladergroen, A.N. Nechaev, V.M. Linkov. Surface functionalization of porous ZrO2–TiO2 membranes using gamma-aminopropyltriethoxysilane in palladium electroless deposition, Applied Surface Science 254 (2008) 3211-3219
- M. Williams, A.N. Nechaev, M.V. Lototsky, V.A.Yartys, J.K.Solberg, R.V.Denys, C.Pineda, Q.Li, V.M.Linkov. Influence of aminosilane surface functionalization of rare earth hydride-forming alloys on palladium treatment by electroless deposition and hydrogen sorption kinetics of composite materials, Materials Chemistry and Physics 115 (2009) 136-141
- M. Williams, M. V. Lototsky, V. M. Linkov, A. N. Nechaev, J. K. Solberg, V. A.Yartys. Nanostructured surface coatings for the improvement of AB5-type hydrogen storage intermetallics, International Journal of Energy Research 33(13) (2009) 1171-1179
- M Williams, M. Lototsky, A. Nechaev, V.Yartys, J.K.Solberg, R.V.Denys,, V.M.Linkov. Palladium mixed-metal surface-modified AB5-type intermetallides enhance hydrogen sorption kinetics, South African Journal of Science 106(9/10) (2010) Article # 310
- M.V. Lototsky, M. Williams, V.A. Yartys, Ye.V. Klochko, V.M. Linkov. Surface-modified advanced hydrogen storage alloys for hydrogen separation and purification, Journal of Alloys and Compounds 509S (2011) S555-S561
- M. Lototskyy, K.D. Modibane, M. Williams, Ye. Klochko, V. Linkov, B.G. Pollet. Application of surface-modified metal hydrides for hydrogen separation from gas mixtures containing carbon dioxide and monoxide, Journal of Alloys and Compounds 580 (2013) S382-S385
- K.D. Modibane, M. Williams, M. Lototskyy, M.W. Davids, Ye. Klochko, B.G. Pollet. Poisoning-tolerant metal hydride materials and their application for hydrogen separation from CO2 / CO containing gas mixtures, International Journal of Hydrogen Energy 38 (2013) 9800-9810

Ti-based MH materials: *patents* and main publications

- *M.Lototskyy, M.W.Davids. Method for preparing hydride-forming alloys, ZA2012/03824*
- *M.Lototskyy, M.W.Davids, B.G. Pollet, V. Linkov, Y.Klochko. Metal Hydride Bed, Metal Hydride Container, and Method for the Making thereof, PCT/IB2015/054321*
- M.W.Davids, M.Lototskyy. Influence of oxygen introduced in TiFe-based hydride forming alloy on its morphology, structural and hydrogen sorption properties, International Journal of Hydrogen Energy 37 (2012) 18155-18162
- M.W. Davids, M. Lototskyy, B.G. Pollet. Manufacturing of hydride-forming alloys from mixed titanium – iron oxide, Advanced Materials Research 746 (2013) 14-22

Mg-based nanocomposites : *patent* and main publications

- *M.W.Davids, M.Lototskyy, M.Williams, J.M.Sibanyoni, B.G.Pollet, V.M.Linkov. Method for preparation of hydride forming material on the basis of nanostructured magnesium hydride, ZA 2012/08851*
- Y.Wu, M.V.Lototsky, J.K Solberg, V.A.Yartys, W.Hana, S.X. Zhou. Microstructure and novel hydrogen storage properties of melt-spun Mg–Ni–Mm alloy; Journal of Alloys and Compounds 477 (2009) 262–266
- M. V. Lototsky, R. V. Denys, V. A. Yartys. Combustion-type hydrogenation of nanostructured Mg-based composites for hydrogen storage; Int. J. Energy Research, 33 (13) (2009) 1114-1125
- R.V. Denys, A.B. Riabov, J.P. Maehlen, M.V. Lototsky, J.K. Solberg, V.A. Yartys. In situ synchrotron X-ray diffraction studies of hydrogen desorption and absorption properties of Mg and Mg–Mm–Ni after reactive ball milling in hydrogen; Acta Materialia 57 (2009) 3989–4000
- Y. Wu, M.V. Lototsky, J.K. Solberg, V.A. Yartys. Microstructural Evolution and Improved Hydrogenation-Dehydrogenation Kinetics of Nanostructured Melt-Spun Mg-Ni-Mm Alloys; Journal of Alloys and Compounds 509S (2011) S640–S645
- Y. Wu, M.V. Lototskyy, J.K.Solberg, V. A. Yartys. Effect of microstructure on the phase composition and hydrogen absorption-desorption behaviour of melt-spun Mg-20Ni-8Mm alloys, International Journal of Hydrogen Energy 37 (2012) 1495-1508
- M. Lototskyy, J.M. Sibanyoni, R.V. Denys, M. Williams, B.G. Pollet, V.A. Yartys. Magnesium-carbon hydrogen storage hybrid materials produced by reactive ball milling in hydrogen, Carbon 57 (2013) 146-160
- M. Williams, J.M. Sibanyoni, M. Lototskyy, B.G. Pollet. Hydrogen absorption study of high-energy reactive ball milled Mg composites with palladium additives, Journal of Alloys and Compounds 580 (2013) S144-S148
- M. Lototsky, M.W. Davids, J.M. Sibanyoni, J. Goh, B.G. Pollet. Magnesium-based hydrogen storage nanomaterials prepared by high energy reactive ball milling in hydrogen at the presence of mixed titanium – iron oxide, Journal of Alloys and Compounds 645 (2015) S454-S459

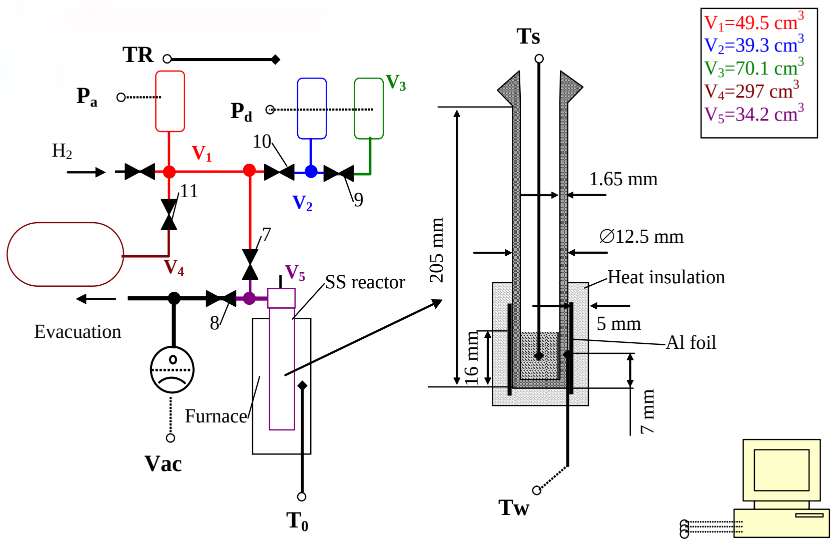
MH H_2 compressors: *patents* and main publications

- *M.Lototskyy, V.M.Linkov. Hydride container, Patent ZA2009/02427*
- *M.Lototskyy, Ye.Klochko, V.M.Linkov. Metal hydride hydrogen compressor, WO 2012/114229 Al: Patent ZA2011/01351*
- *M.Lototskyy, M.W.Davids, B.G. Pollet, V.Linkov, Y.Klochko. Metal hydride bed, metal hydride container, and method for the making thereof, Patent Applications ZA2014/04205, PCT/IB2015/054321*
- *M.V. Lototskyy, D.Swanepoel, M.W.Davids, Y.Klochko, B.J. Bladergroen, V.M. Linkov. Multistage metal hydride hydrogen compressor, Patent Application ZA2015/01837*
- M.Lototskyy, Ye.Klochko, V.Linkov, P.Lawrie, B.G.Pollet. Thermally Driven Metal Hydride Hydrogen Compressor for Medium-Scale Applications, Energy Procedia 29 (2012) 347-356
- M.V. Lototskyy, V.A. Yartys, B.G. Pollet, R.C. Bowman, Jr. Metal hydride hydrogen compressors: a review, International Journal of Hydrogen Energy 39 (2014) 5818-5851
- V. Yartys, M. Lototskyy, V. Linkov, D. Grant, A. Stuart, J. Eriksen, R. Denys, R.C. Bowman, Jr. Metal hydride hydrogen compression: recent advances and future prospects, Appl. Phys. A (2016) 122: 415, DOI 10.1007/s00339-016-9863-7
- M. Lototskyy, Y. Klochko, M.W. Davids, L. Pickering, D. Swanepoel, G. Louw, B. van der Westhuizen, S. Chidziva, C. Sita, B. Bladergroen, V. Linkov. Industrial-scale metal hydride hydrogen compressors developed at the South African Institute for Advanced Materials Chemistry, Materials Today: Proceedings (2018), in press, DOI 10.1016/j.matpr.2017.12.383

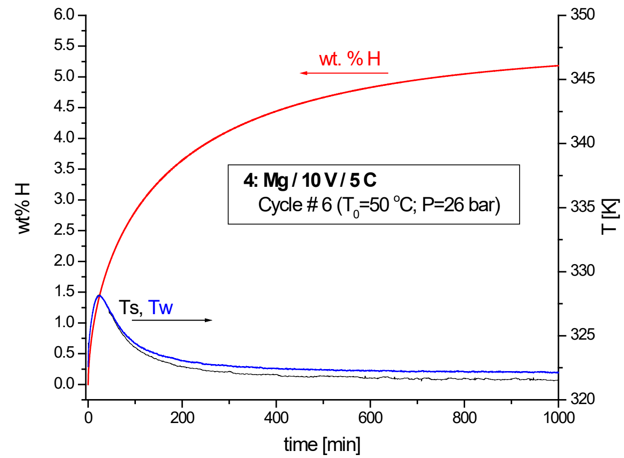
MH H_2 storage / integrated systems: *patents* and main publications

- *M.Lototskyy, V.M.Linkov. Hydride container, Patent ZA2009/02427*
- *M.Lototskyy, I.Tolj, M.W.Davids, B.G Pollet, V.Linkov. Hydrogen storage and supply system integrated with fuel cell power pack, Patent Application ZA2014/08640*
- I.Tolj, M.V. Lototskyy, M.W.Davids, S.Pasupathi, G.Swart, B.G. Pollet. Fuel cell-battery hybrid powered light electric vehicle (golf cart): influence of fuel cell on the driving performance, International Journal of Hydrogen Energy 38 (2013) 10630-10639
- M. Lototskyy, I. Tolj, M.W. Davids, P. Bujlo, F. Smith, B.G. Pollet. “Distributed hybrid” MH–CGH2 system for hydrogen storage and its supply to LT PEMFC power modules, Journal of Alloys and Compounds 645 (2015) S329-S333
- M.V. Lototskyy, M.W.Davids, I.Tolj, Y.V.Klochko, B. Satya Sekhar, S.Chidziva, F.Smith, D.Swanepoel, B.G.Pollet. Metal hydride systems for hydrogen storage and supply for stationary and automotive low temperature PEM fuel cell power modules, International Journal of Hydrogen Energy 40 (2015) 11491-11497
- B. Satya Sekhar, A. Kolesnikov, M. L.Moropeng, M. Lototskyy, B.P.Tarasov, B.G. Pollet. Performance analysis of cylindrical metal hydride beds with various heat exchange options, Journal of Alloys and Compounds 645 (2015) S89-S95
- M.Lototskyy, I.Tolj, M.W.Davids, A.Parsons, Y. Klochko, D.Swanepoel, R.Ehlers, G.Louw, B. van der Westhuizen, F.Smith, B.G. Pollet, C. Sita, V. Linkov. Metal Hydride Hydrogen Storage and Supply Systems for Electric Forklift with low-temperature proton exchange membrane fuel cell Power Module, International Journal of Hydrogen Energy 41 (2016) 13831-13842
- M.V. Lototskyy, I. Tolj, A. Parsons, F. Smith, C. Sita, V. Linkov. Performance of electric forklift with low-temperature polymer exchange membrane fuel cell power module and metal hydride hydrogen storage extension tank, J. Power Sources 316 (2016) 239-250
- M.V. Lototskyy, I. Tolj, L. Pickering, C. Sita, F. Barbir, V. Yartys. The use of metal hydrides in fuel cell applications, Progress in Natural Science: Materials International 27 (2017) 3–20

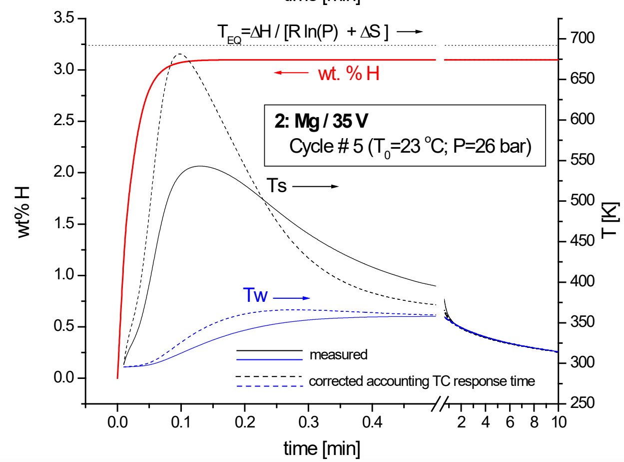
Mg – BCC-V Alloy: Combustion-Type Hydrogenation



Slow



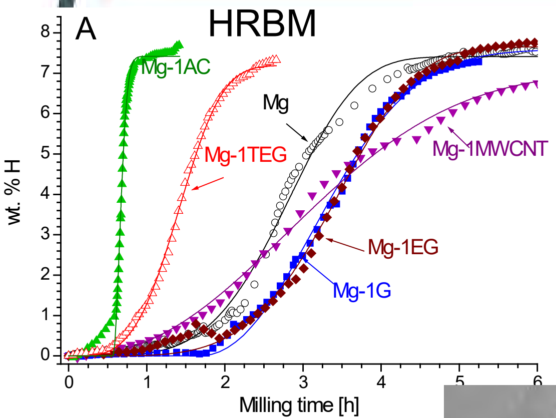
Fast

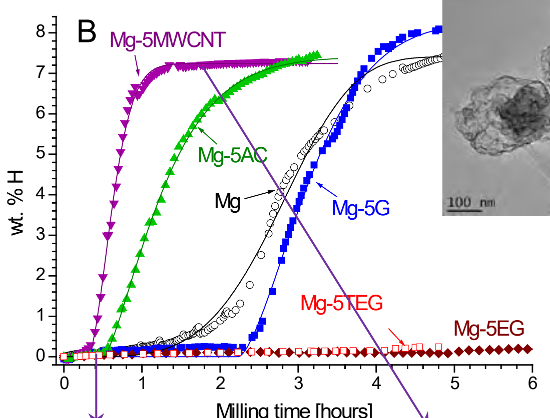


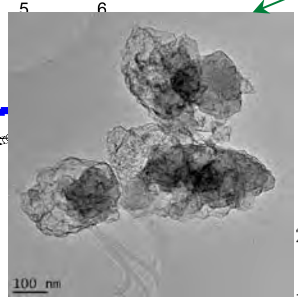
Two re-hydrogenation modes were observed:

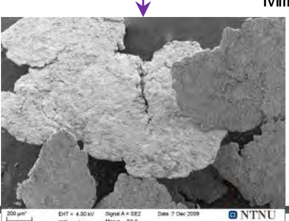
1. In slow mode hydrogenation takes place even at RT and is completed in 10–15 hours; 80–90% of MAX H capacity is achieved.
2. In fast (combustion) mode hydrogenation completes in 5–60 seconds and is accompanied by a significant heat release; sample temperature, Ts, approaches equilibrium value ($Mg \leftrightarrow MgH_2$) for the operating H_2 pressure; 60–65% of MAX H capacity is achieved (80% for Mg / 10V / 5 C).

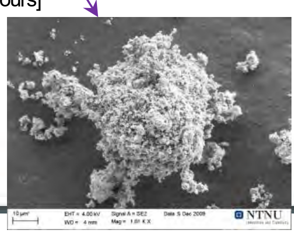
Mg – C

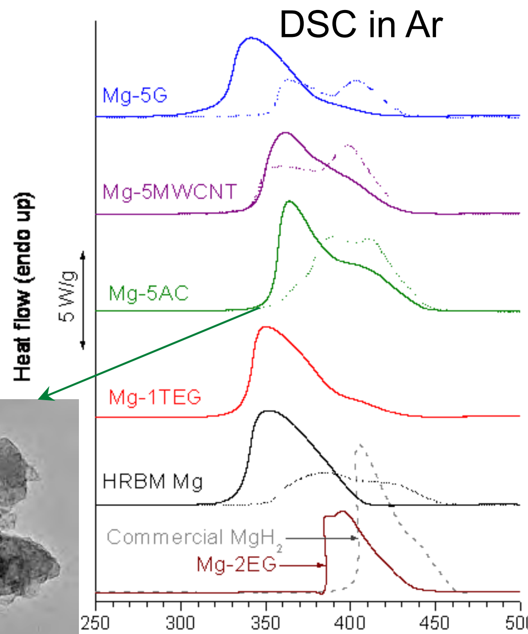


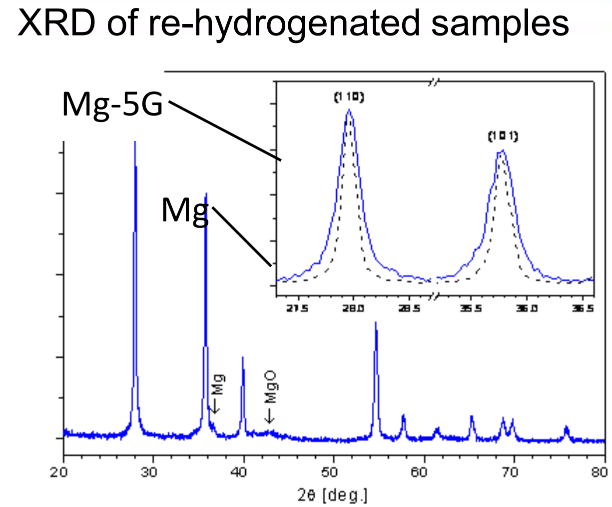


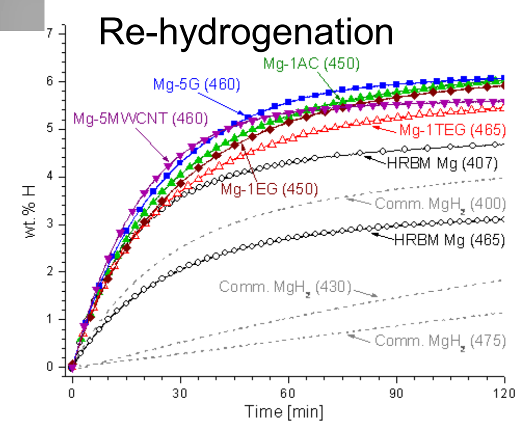


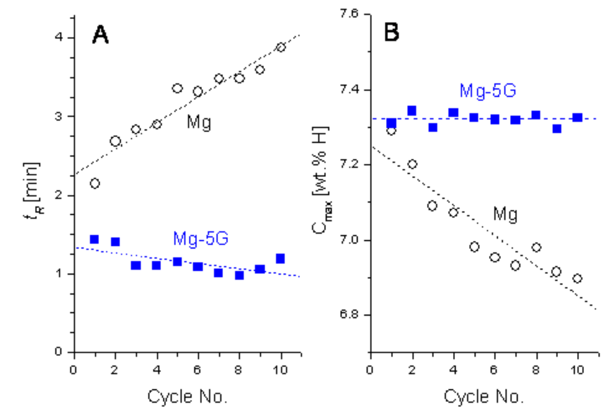












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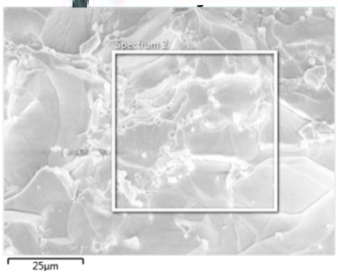
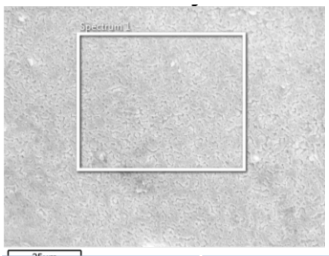
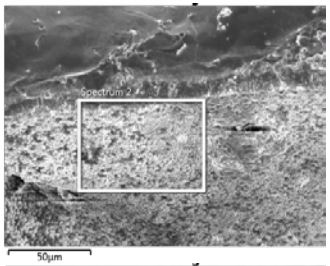
Quality Assurance – Composition (SEM / EDS)



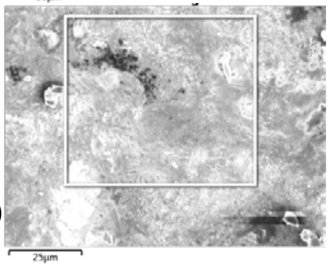
Major phase



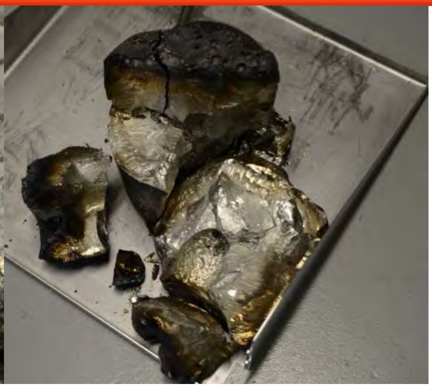
Impurity 1 (side)



Impurity 2 (top)



Impurity 3 (bottom)



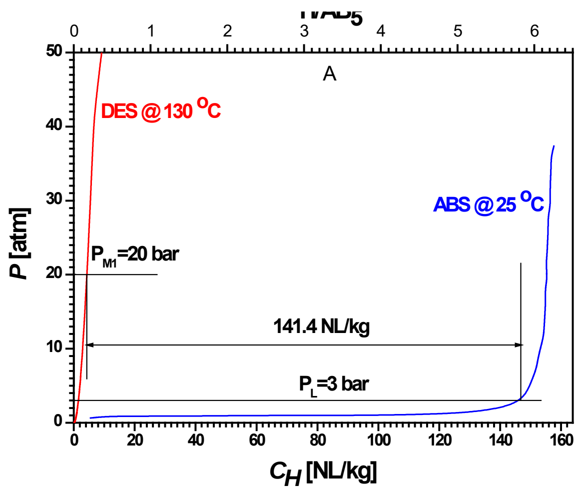
Significant amounts of C and O in the impurity phases (casting in a graphite mould)

Component	Major phase (7 spectra)			Impurity 1 (3 spectra)	Impurity 2 (1 spectrum)	Impurity 3 (1 spectrum)
	Nominal composition [at.%]	Results of analysis [at.%]	Deviation from nominal composition [at.%]	Results of analysis [at.%]	Results of analysis [at.%]	Results of analysis [at.%]
Ti (A)	**18.31**	**18.04 ± 0.72**	**-0.27**	19.47 ± 0.49	17.52	11.22
Zr (A)	**14.98**	**15.15 ± 2.05**	**+0.17**	39.45 ± 0.95	24.77	86.55
Cr (B)	**27.96**	**28.91 ± 1.22**	**+0.95**	22.47 ± 0.18	20.10	1.71
Mn (B)	**12.85**	**12.91 ± 0.65**	**+0.06**	1.58 ± 0.79	22.57	0
Fe (B)	**18.31**	**18.07 ± 0.72**	**-0.24**	13.13 ± 1.18	11.03	0.52
Ni (B)	**6.66**	**6.19 ± 1.23**	**-0.47**	3.9 ± 0.24	4.02	0
Cu (B)	**0.93**	**0.74 ± 0.22**	**-0.19**	0	0	0
B/A	**2.00**	**2.01**		0.70	1.36	0.02

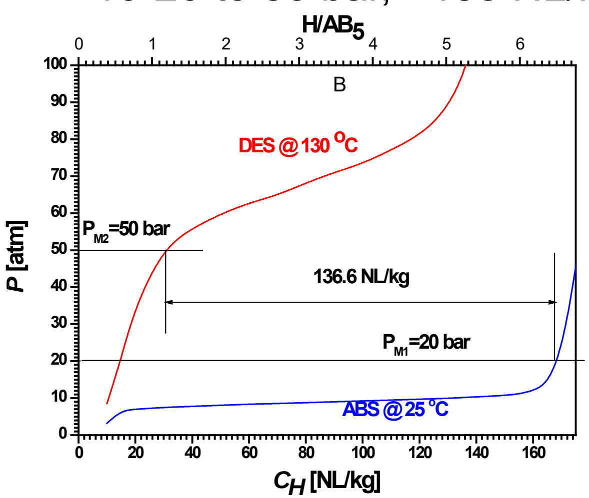
More “pure” casting achieved by the installation of water cooled Cu mould

MH materials for H_2 compression

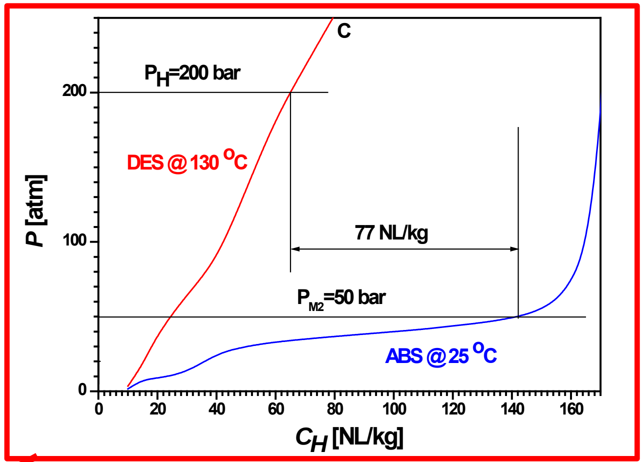
Stage -(1): $LaNi_{4.9}Sn0.1$
3 to 20 bar, ~140 NL/kg

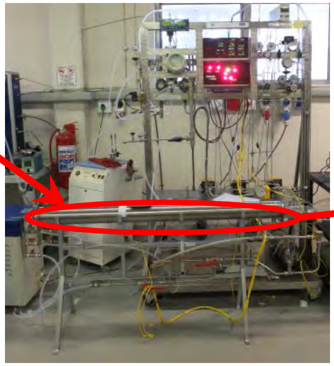


Stage 1(2): $La_{0.8}Ce_{0.2}Ni_5$
10-20 to 50 bar, ~135 NL/kg



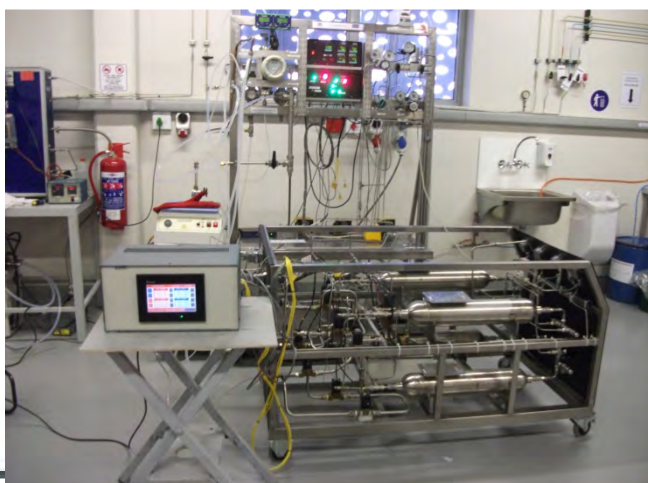
Stage 2(3): AB_{2+x} (A=Ti+Zr; B=Mn+Fe+Cr+Ni)
50 to 200 bar, ~80 NL/kg

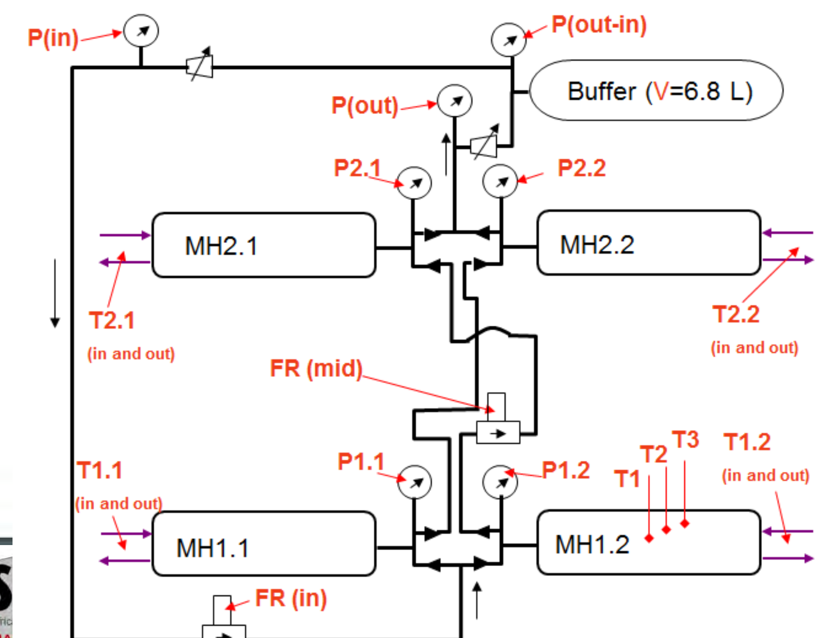




Testing facilities (small- to medium scale)

- Possibility to test both MH containers and MH compressors (1-200 bar, up to 6 m^3/h);
- Heating:
  - Steam (up to 140°C / 10 kg/h);
  - Pressurised water (up to 180 °C / 20 L/min);
- Cooling: tap water (~20 °C, up to 20 L/min);
- Data acquisition (P, FR, T) using LabView.





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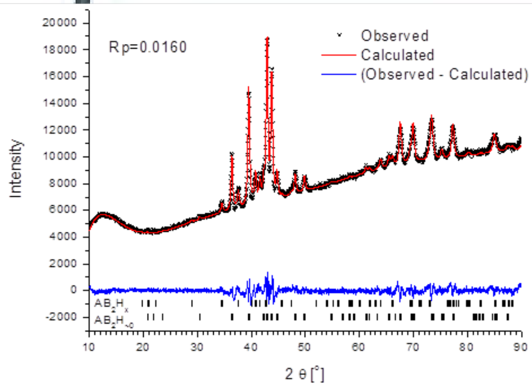
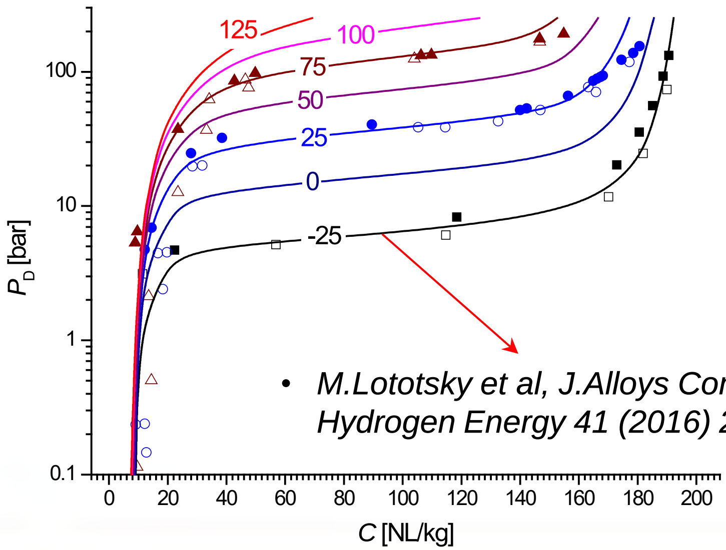
MH material



	Alloy	Hydride	
	AB_2	$AB_2H_{\sim 0}$	AB_2H_x
a [Å]	4.9296(3)	4.9340(2)	5.1871(8)
c [Å]	8.0723(9)	8.0858(4)	8.474(3)
V [Å^3]	169.88(2)	170.475(9)	197.46(5)
$\Delta V/V_0$ [%]	–	0.35	16.23
ρ [g/cm^3]	6.884	6.678	5.765

Used for the determination of safe MH load into containers



- *M.Lototsky et al, J.Alloys Compds 356–357 (2003) 27–31; Int. J. Hydrogen Energy 41 (2016) 2739-2761*

- **AB_2: A=(Ti,Zr), B=(Fe,Cr,Mn,Ni,V…).**
- Tuning of PCT properties by the variation of the component composition.
- H_2 pressures >10 bar at the temperatures above 0 °C.
- At T > 125 °C most of hydrogen is desorbed at P > 200 bar.
- Suitable for both H_2 storage (T=0–50 °C, P>10 bar) and compression (T=20–140 °C, P=30–200 bar).
- **Same material for H_2 storage (MH extension tank) and H_2 compression (refuelling).**