Hydrogen

WP3 reporting

Measuring the hydrogen capacity of hydride tanks

Oliver Büker | Benoit Delobelle | Olivier Gillia | Rodrigo Perez

RISE

MAHYTEC
Innovative Hydrogen Solutions

liten
cea tech

FUNDACIÓN PARA EL
DESARROLLO DE LAS NUEVAS
TECNOLOGÍAS DEL HIDRÓGENO
EN ARAGÓN

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

PLAN

- Introduction – Presentation of hydride storage
- ISO16111
- Different way to measure the hydrogen capacity of a tank
- Thermal mass flowmeter : details
- Tank manufactured and initially tested by Mahytec
- Test bench and results from FHA
- Test bench and results from CEA
- Recommendations for optimized testing devices
- Conclusions and perspectives

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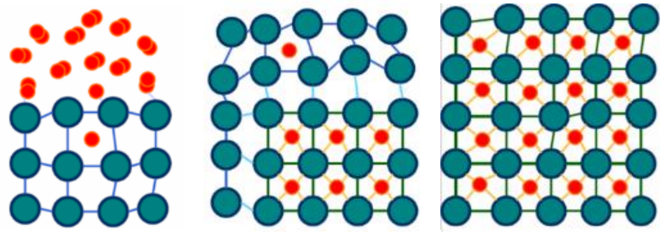
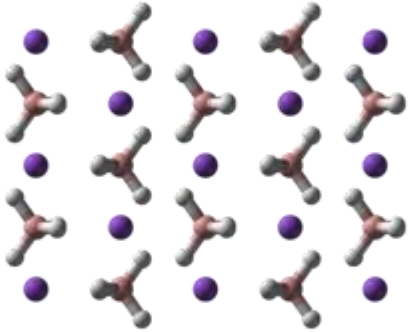
A few words on hydride storage





NaBH4

- Elements
  - Alloys
    - Solid solution
    - Intermetallic
      - AB_2
      - AB_5
      - AB
      - A_2B
  - Complexes
    - TM
    - non TM
      - $NaAlH_4$
      - $NaBH_4$
      - $LiBH_4$

metallic link (reversible)

ionic link (tricky reversibility)

Intermetallic Hydrides

❖ no progress expected in capacity, but work well

➔ research of low cost

⇨ Search for low cost precursor (i) impurities

(ii) fundamental research : influence of impurities on the absorption capacities

Complex Hydrides

❖ potential progress or rupture, but not working well

➔ alanates, LiBH4 + MgH2, LiNH2

⇨ Desequilibrate the thermodynamics and obtain reversibility

- nanoconfinement
- catalysis
- hybridation of materials (LiBH4+MgH2)

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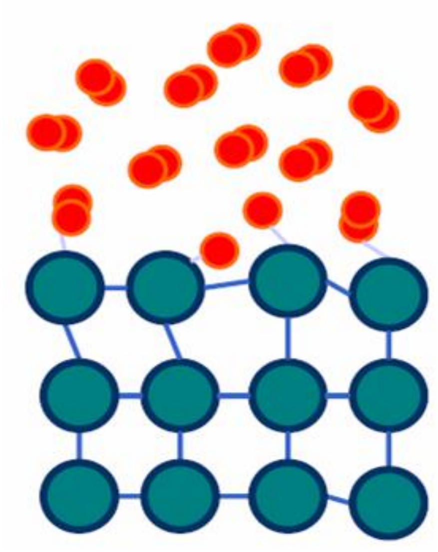
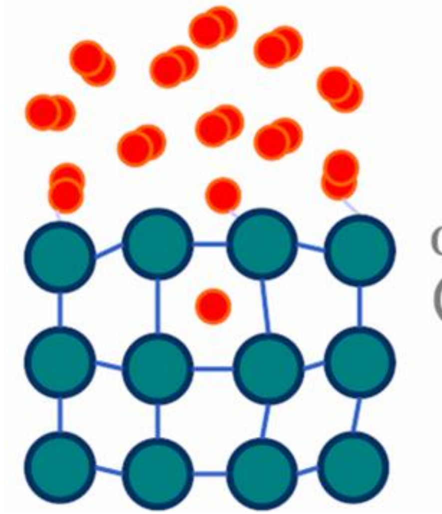
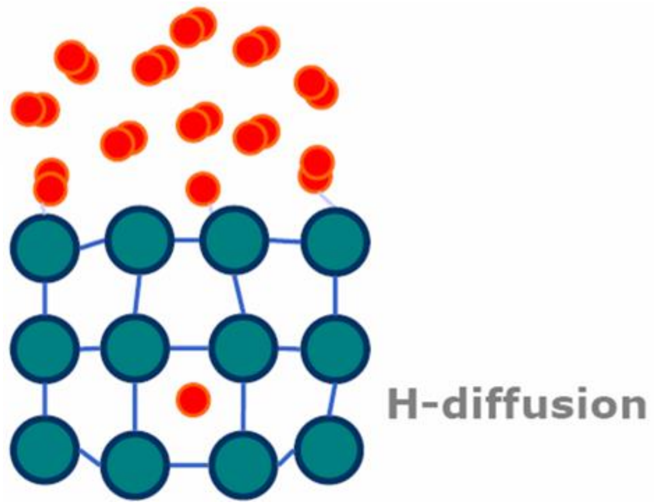
Hydride storage - principle







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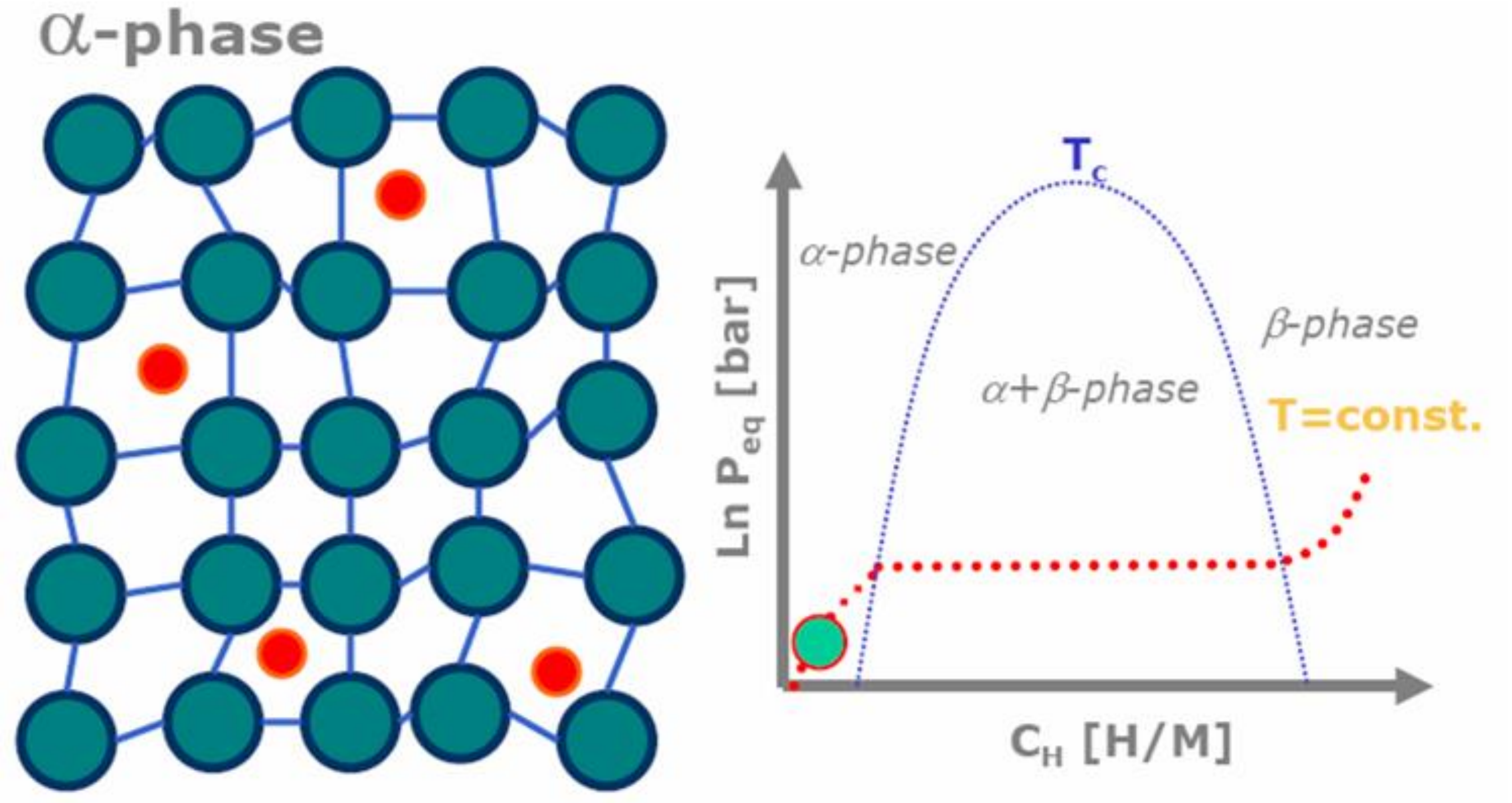
Hydride storage - principle



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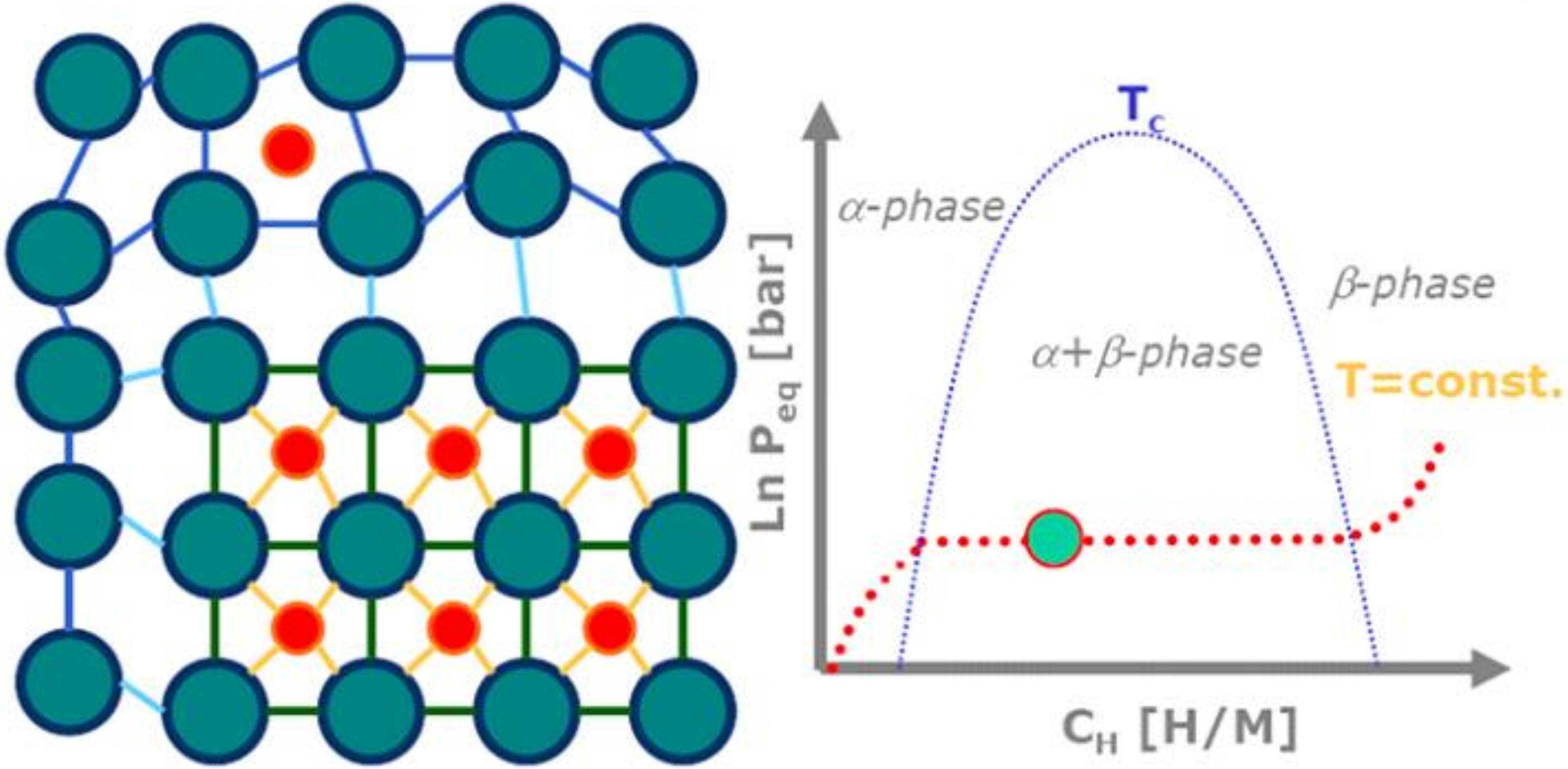
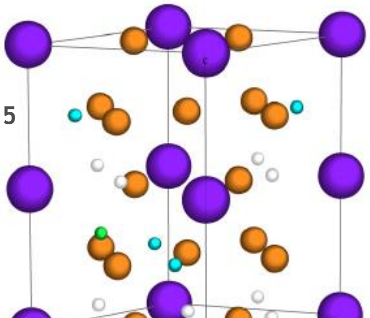
Hydride storage - principle

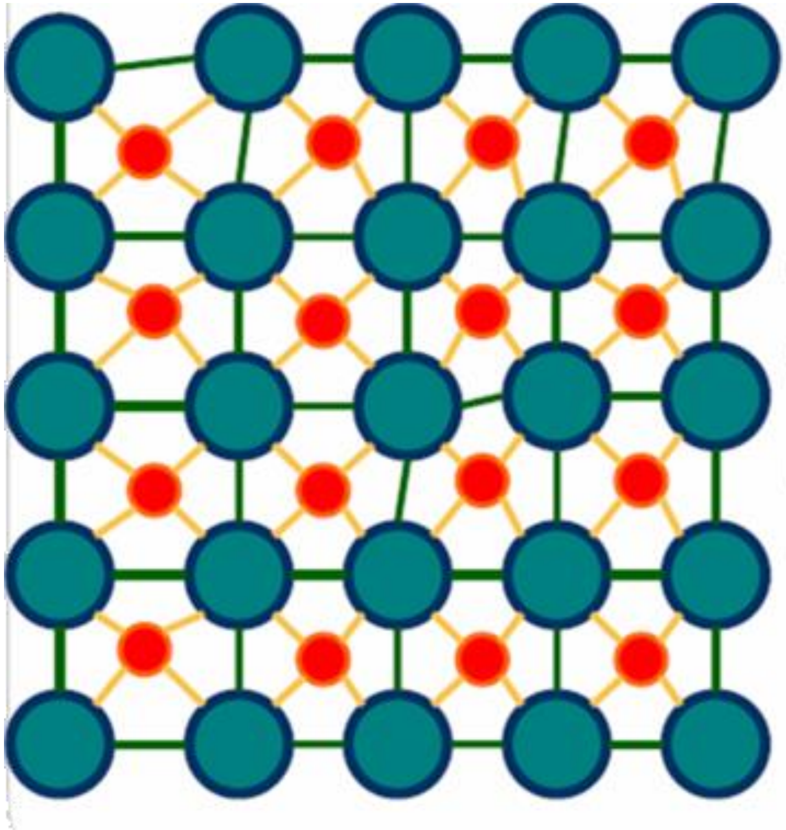


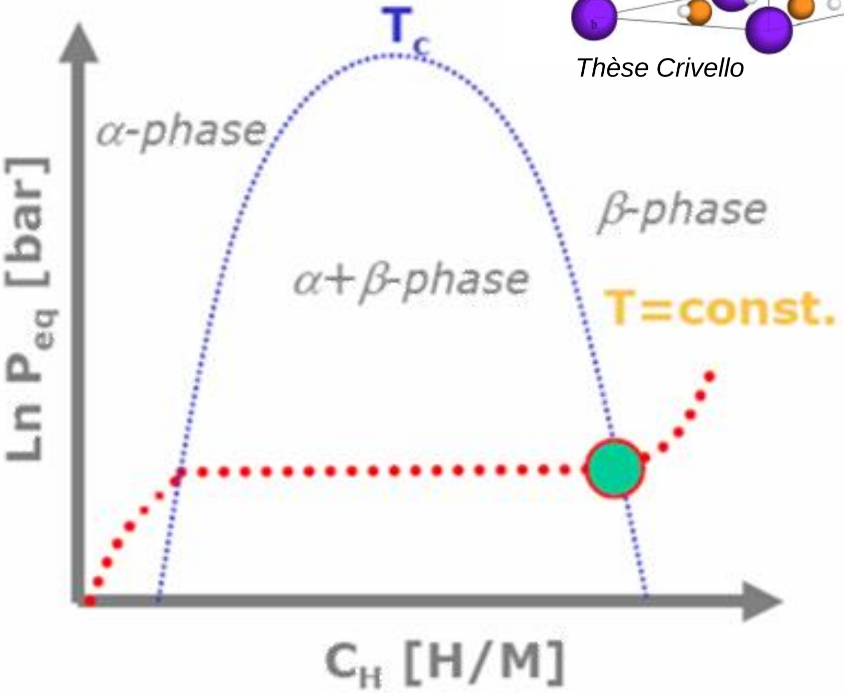
Hydride storage - principle

$LaNi_5H_5$



Thèse Crivello





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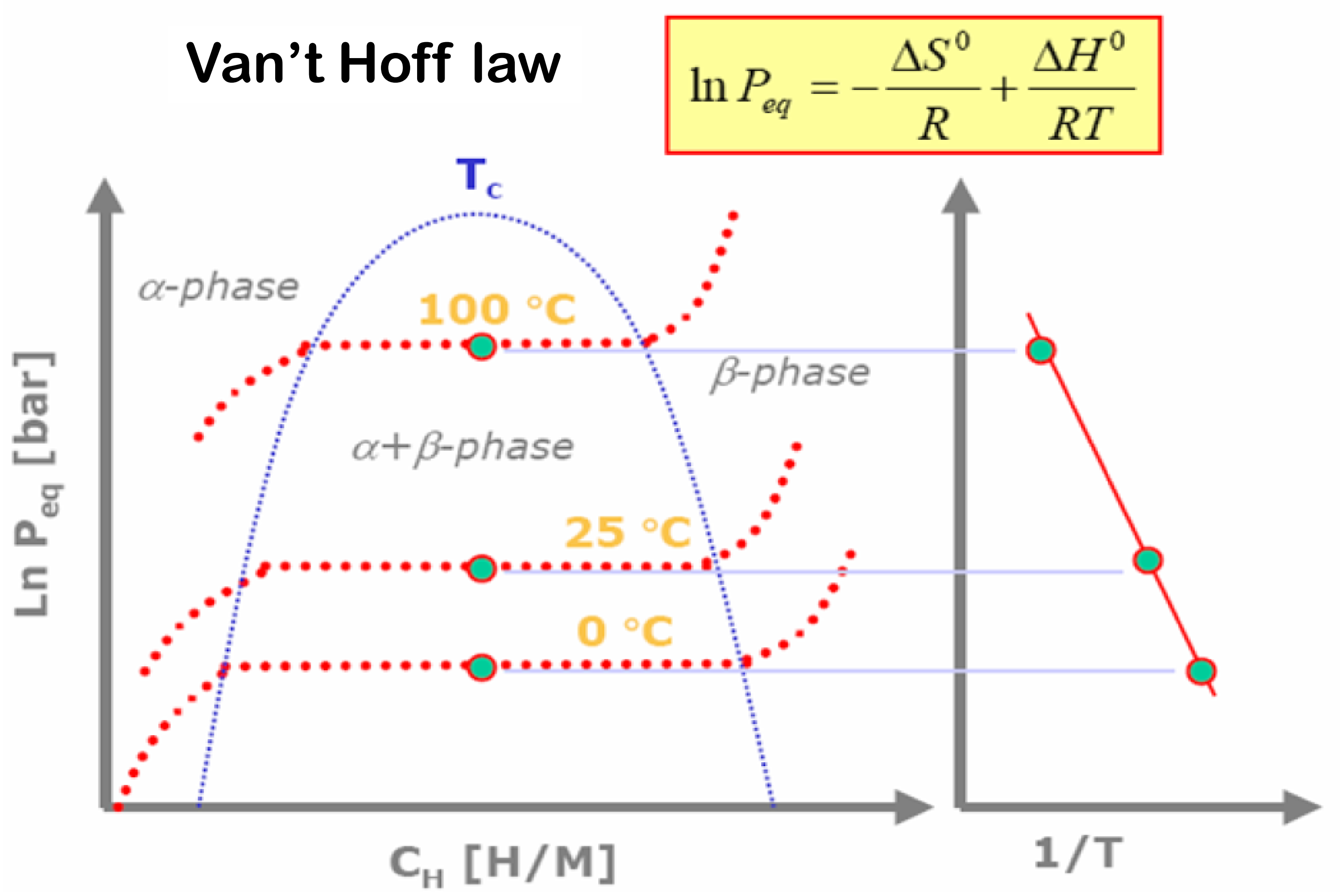
Hydride storage - principle



Van’t Hoff law

$$\ln P_{eq} = -\frac{\Delta S^0}{R} + \frac{\Delta H^0}{RT}$$

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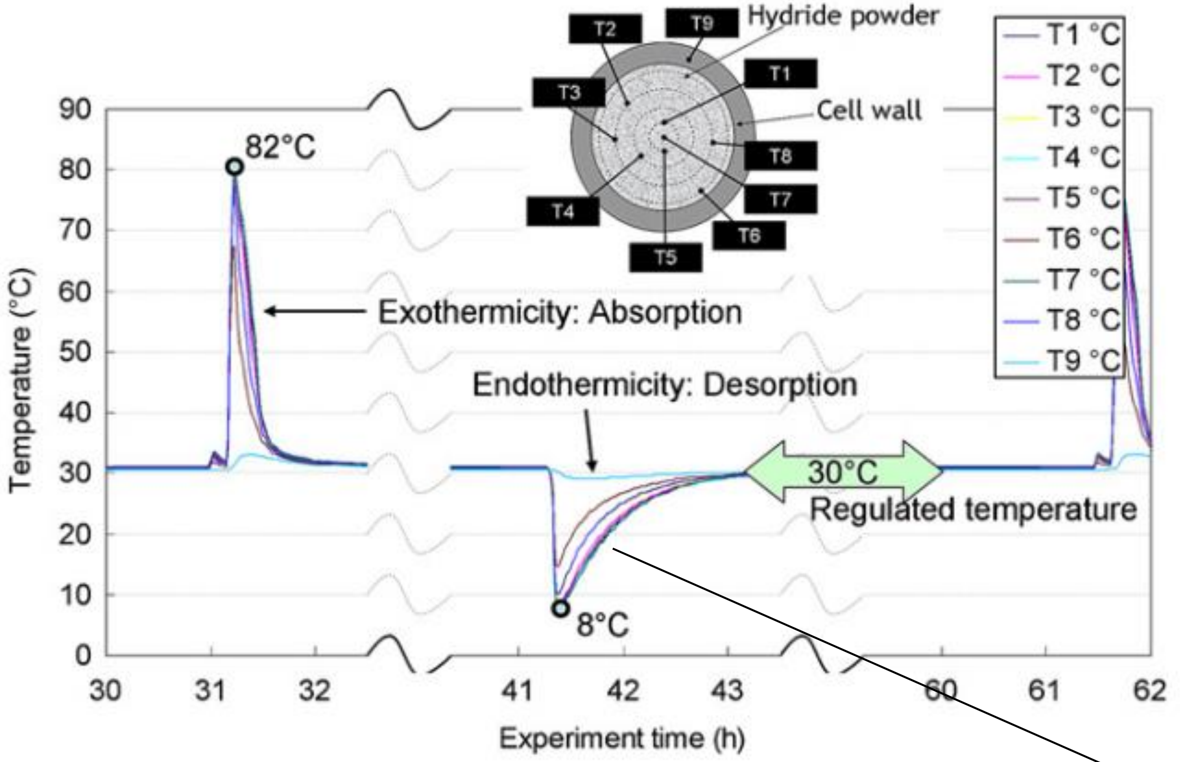
Hydride storage – exo/endo-thermicity

Matériau : TiVCr (BCC) – 0 – 40 bars at 30°C



Article : B. Charlas, O. Gillia, P. Doremus, D. Imbault, Int. J. H. E, 2012

Cooling due to desorption

➔ **security if leaks : auto-cooling and stopping**

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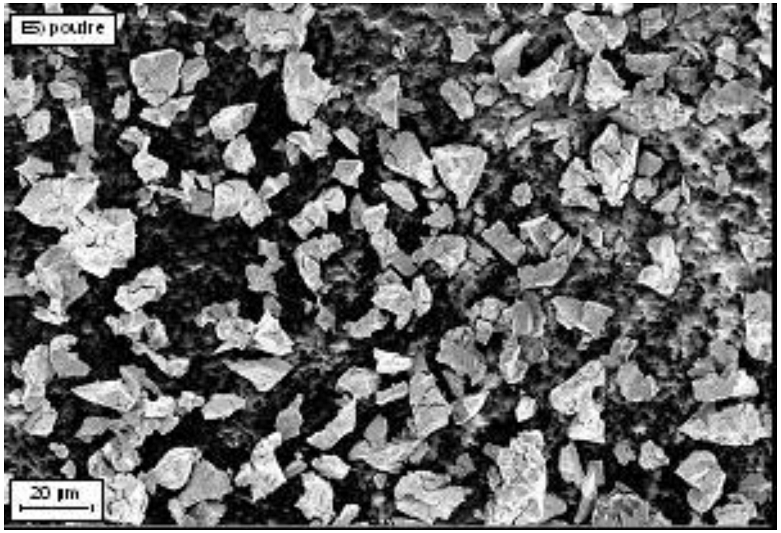
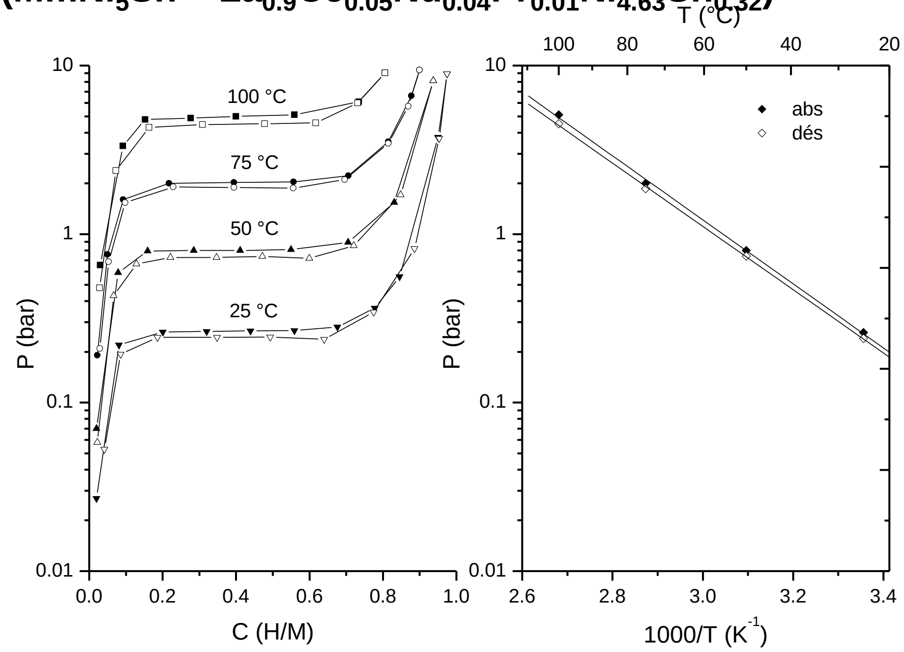
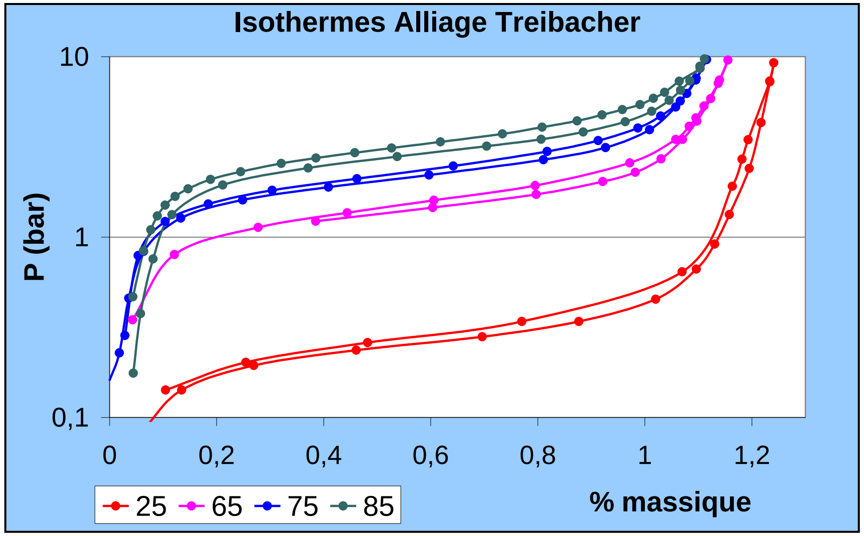
Hydride storage - principle

MmNi5 (LaNi5) laboratory alloy



($MmNi_5Sn = La_{0.9}Ce_{0.05}Nd_{0.04}Pr_{0.01}Ni_{4.63}Sn_{0.32}$)





Industrial alloy of the same formulation

M. Botzung Ph.D

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Hydrides – somes examples

Family	Compound	Max weigth capacity (%)	Temp. (°C) at P=1 bar	Kinetics	ΔH (kJ/mol)
AB	FeTi	1.8	-8	Fast	-28.1
AB_5	$LaNi_5$	1.49	12	Very fast	-30.8
AB_2	$Ti_{0.98}Zr_{0.02}V_{0.43}$ $Fe_{0.09}Cr_{0.05}Mn_{1.5}$	1.9	-28	Very fast	-27.4
BCC	$(V_{0.9}Ti_{0.1})_{0.95}Fe_{0.05}$	3.7	36	Fast	-43.2
A_2B	Mg_2Ni	3.6	255	Mean	-64.5
complexe	NaAlH4	7.5	180	Mean	-70
Single element	Mg	7.6	279	Slow	-74.5

source : Sandrock review paper, 2003

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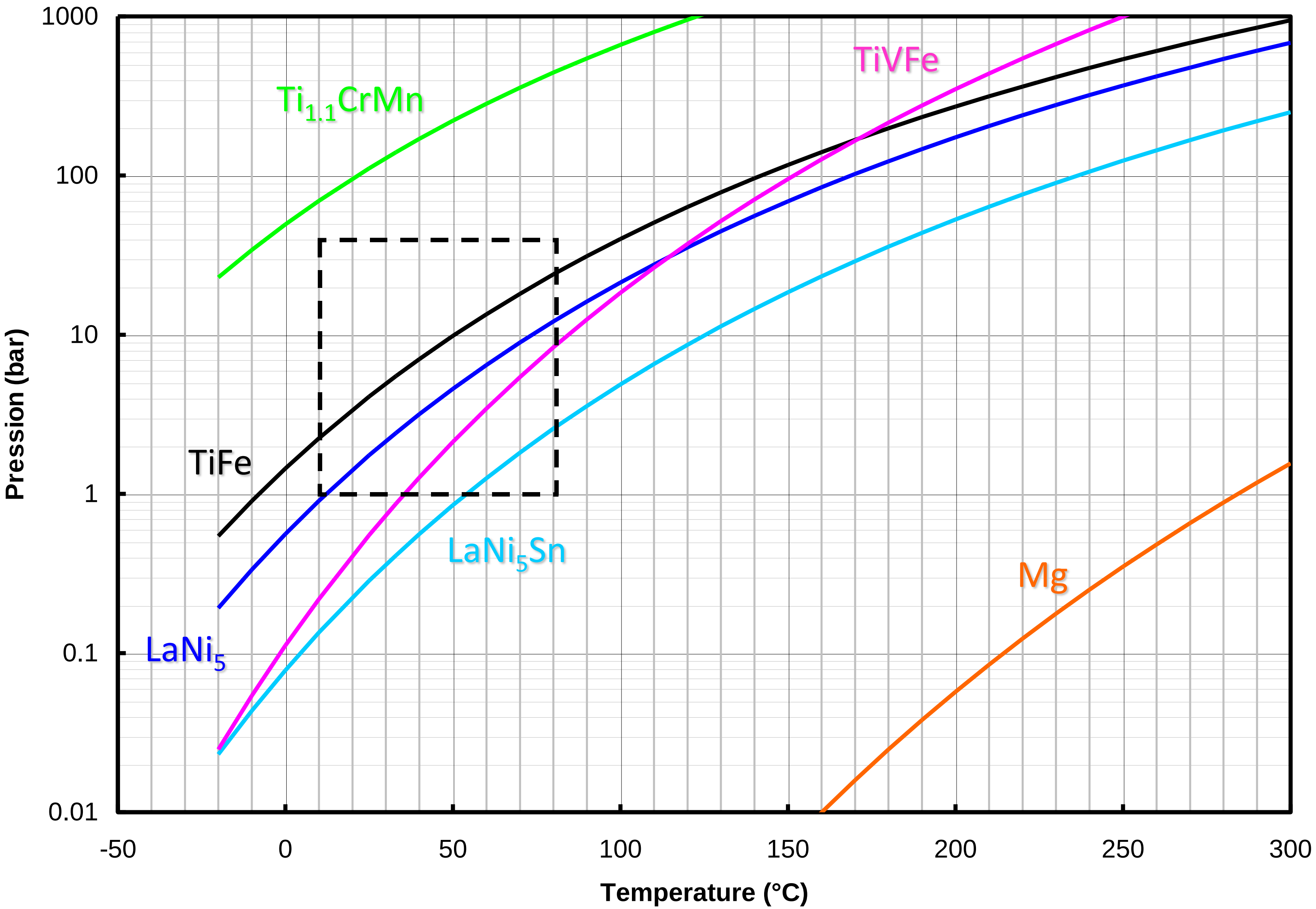
Hydrides – somes examples



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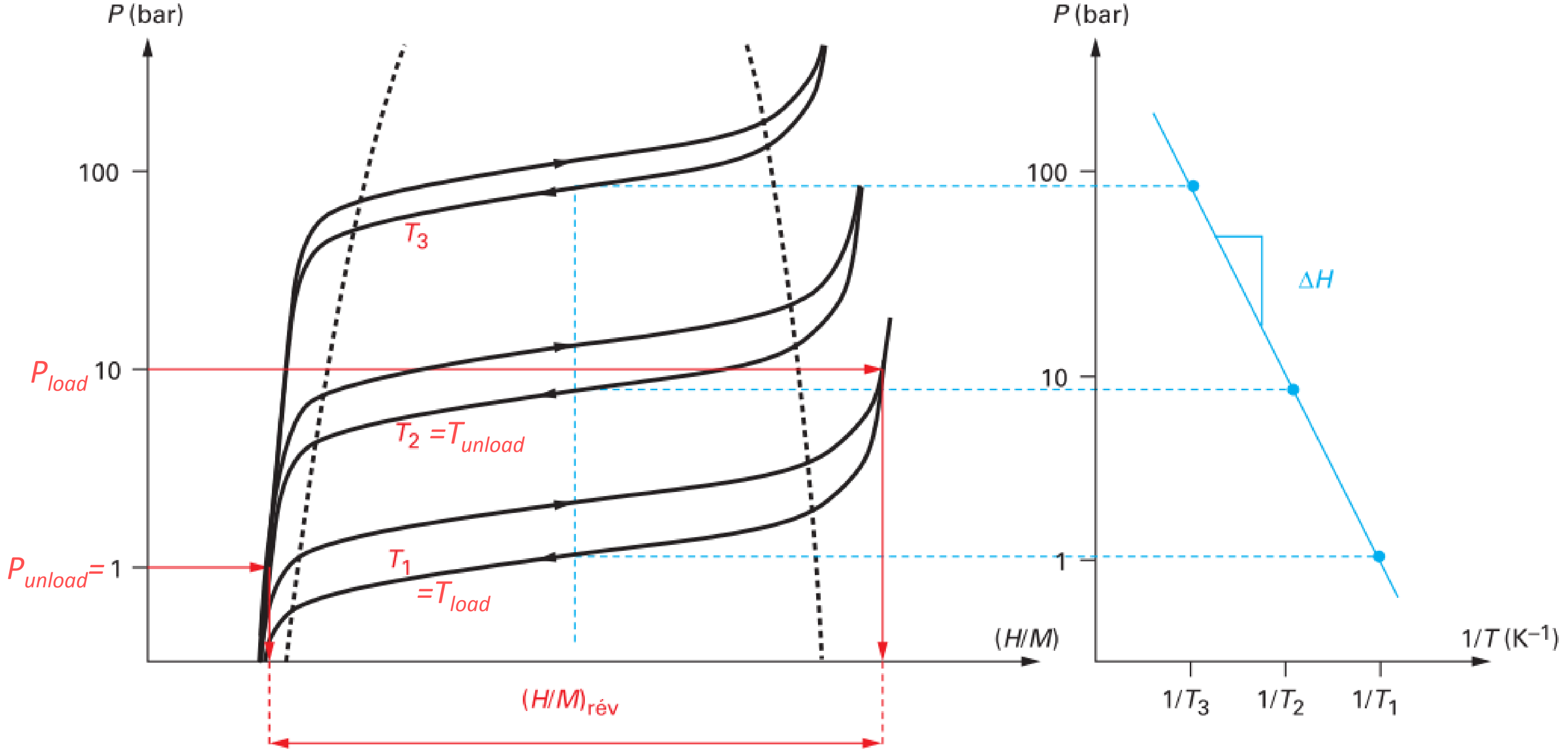
Hydride reversible capacity

The hydride reversible capacity is linked to **operating conditions**

operating temperature range [T_{load}:T_{unload}]
operating pressure range [P_{load}:P_{unload}]

! in ISO16111, the operating temperature range differs from service temperature range which is at least [-40:65] °C



Hydride reversible capacity

e.g. RC : rated capacity on ISO16111

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Piloting the hydride tank

Pressure piloting

T = cst = T1 or T2

P = P_{unload} to P_{load}

Temperature piloting

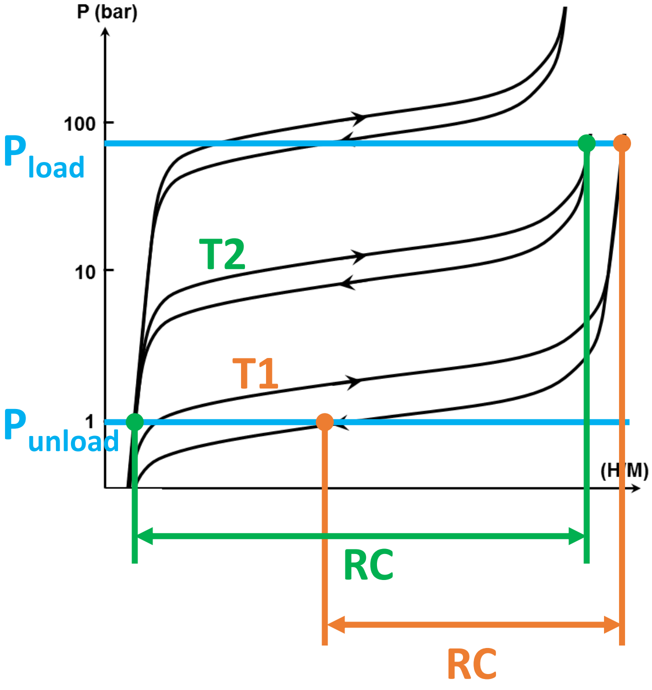
T = T1 to T3

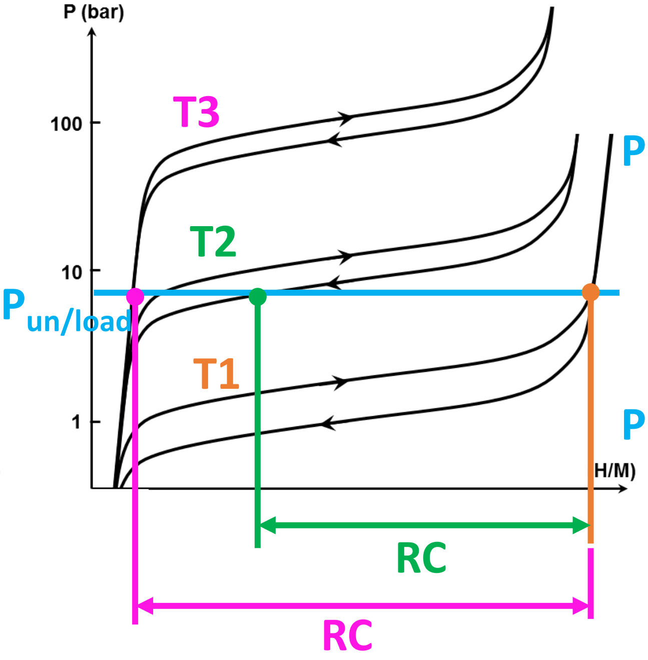
P = $P_{un/load}$

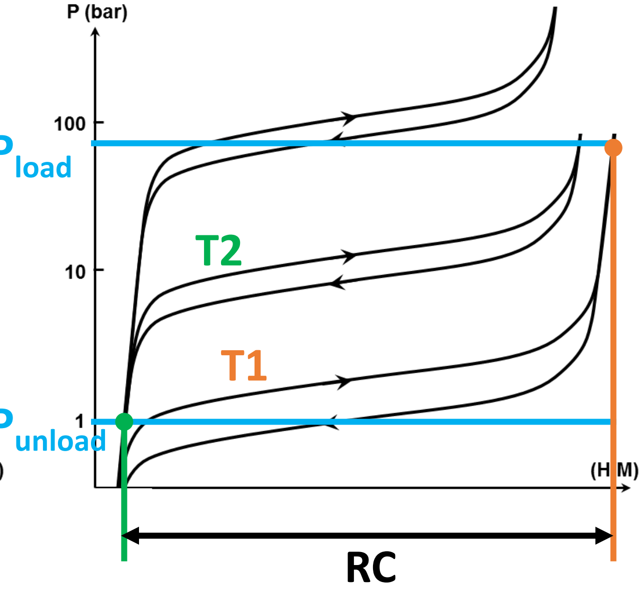
Both

T = T1 to T2

P = P_{unload} to P_{load}







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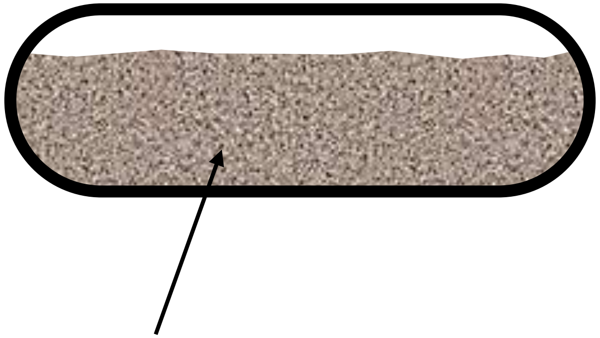
Tank reversible capacity

Tank reversible capacity > Material reversible capacity

Tank reversible capacity shall include the hydrogen in the hydride as well as the hydrogen in gaseous form



$$V_{gas} = V_{sky} + V_{porosity}$$

$$\begin{tikzcd}
n_{tot} = & n_{hyd} \arrow[d] & + & n_{gas} \arrow[d] \\
& RC & & n_{gas} = \dfrac{P_{load} V_{gas}}{Z(T) R T}
\end{tikzcd}$$

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ISO 16111

INTERNATIONAL STANDARD

ISO 16111

First edition
2008-11-15

Transportable gas storage devices — Hydrogen absorbed in reversible metal hydride

Appareils de stockage de gaz transportables — Hydrogène absorbé dans un hydrure métallique réversible

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From ISO 16111

P

RCP : Rated charging pressure ensure $\sigma < \sigma_{design}^{max}$

RCP Pressure corresponding to design stress limit σ_{design}^{max}

PT Test pressure of the shell (<250 bar)

MDP Maximum developped pressure <0,8 PT
(generally at 65°C)

Design strength :

$$\sigma_{design}^{max} = \sigma_{P=1,25MDP} + \sigma_{th} + \sigma_{w} + \sigma_{shock} + \sigma_{hydride\ swell} + \sigma_{others}$$
$$= PT$$

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From ISO 16111

Fire test

- 1 MH tank

Burst test

- 3 MH tank

Drop test

- 1 MH tank

Leak test

- 1 MH tank

Hydrogen cycling

- 5 to 6 MH tank

Shut-off valve impact test

- 3 MH tank

Thermal cycling test

- 5 to 6 MH tank

+

Batch test

- Pressurize to destruction

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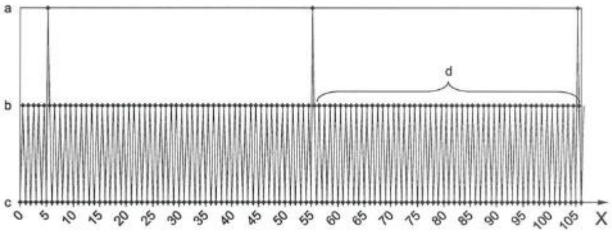
From ISO 16111

Cycle test

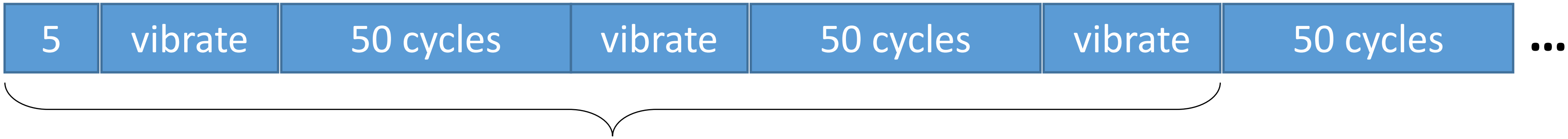
for those used in a single orientation : 5 tanks in that orientation

for those used in a single orientation : 2x3 tanks in perpendicular orientation, horizontal and vertical

cycle between <5% of RC and >95% of RC



at pressure P=RCP for loading (and for unloading ?)



minimum number of cycles

repeat until if strain measured at loaded state :

- **for gages with strain > 0,5 strain design limit is stable ➔ success**
- **is exeeding the strain design limit or plastification is observed ➔ failure**

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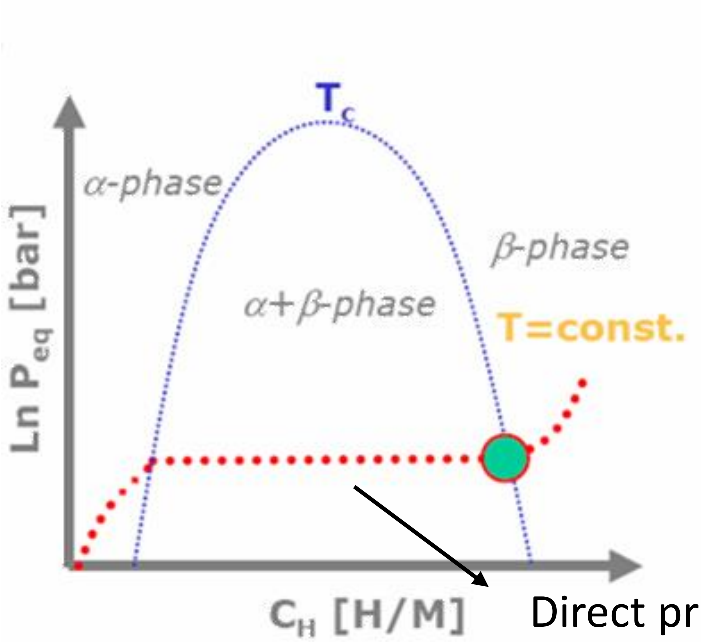
Measurement techniques

Measurement techniques

- Direct Gravimetric technique
- Direct Volumetric technique
- Flow integration technique
  - Mass flow technique
  - Volume flow technique



Direct pressure measurement is not relevant

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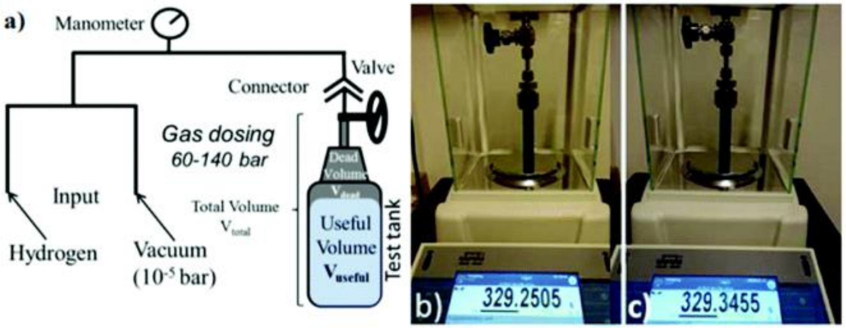
Measurement tech. – Mass measurement

The idea is simply to weigth the absorbed gas (hydrogen)



Need very precise scale as H2 is light :
AB tank : 0,8 kg H2 / 100 kg system

A lot of uncertainties coming from :

- weigth and stiffnesses of connection
- air movement around the tank

SCALES

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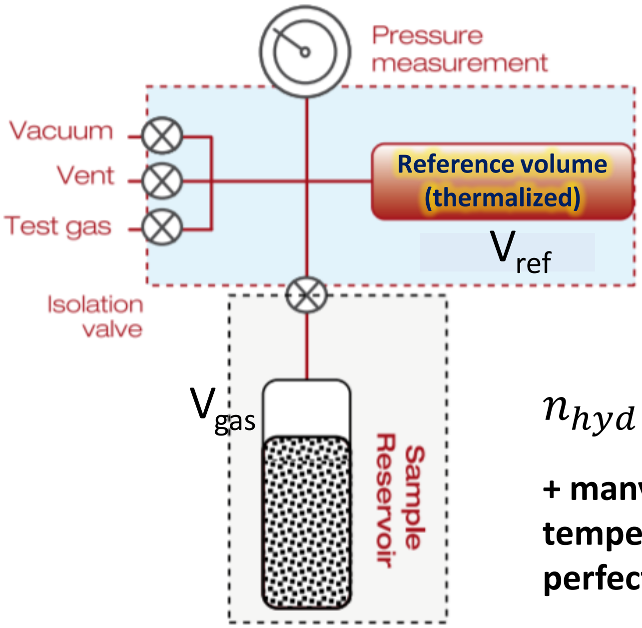
Measurement tech. - Volumetric method

Sievert method, based on 2 points:

- ➢ **Calibrated volumes**
- ➢ **Pressure measurement**

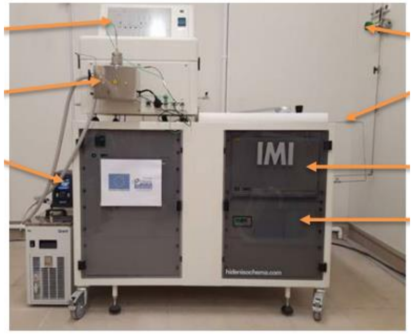


$$n_{hyd} \propto (P_{initial} - P_{final}) V_{ref}$$

+ many corrections on V_{gas}, temperature, sub-volumes, non perfect hydrogen gas

- ➢ **Be careful of (long) transcient thermal effects**

Commercial PCT products examples:



➔ more often used as incremental to precisely determine the PCT curve

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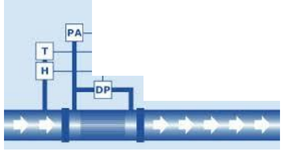
Measurement techniques

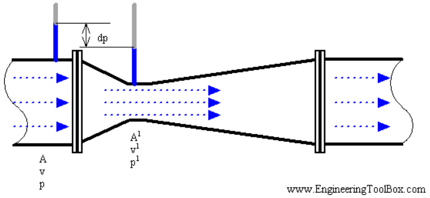
Flow integration method

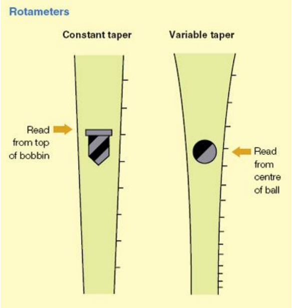
Volume flow techniques

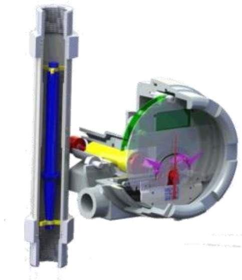
Others

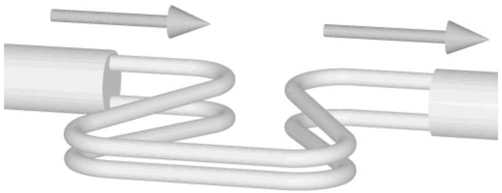
- Pressure drop
- Rotameter
- Coriolis
- Others (US, deflection,…)

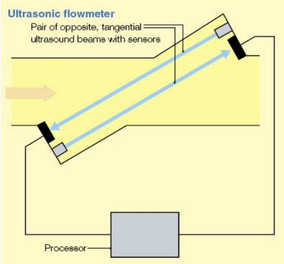


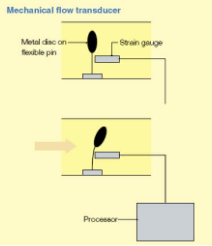












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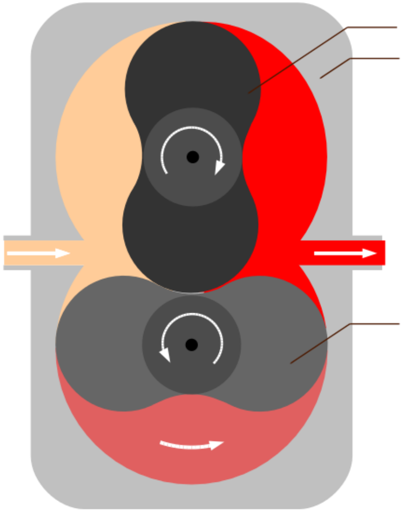
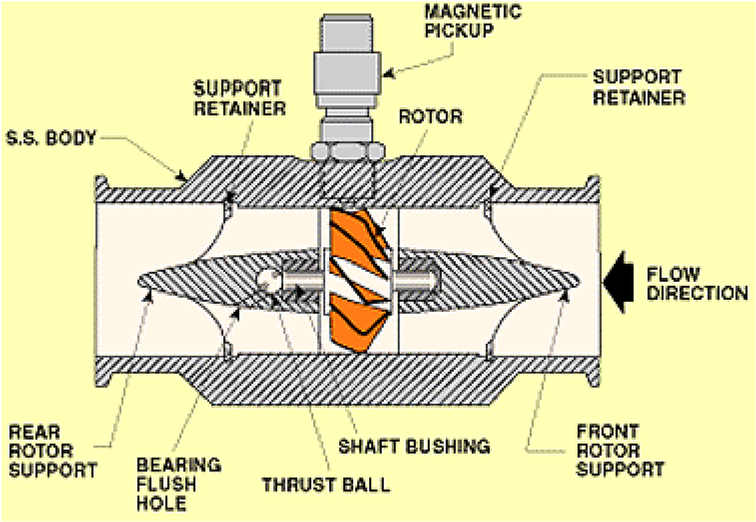
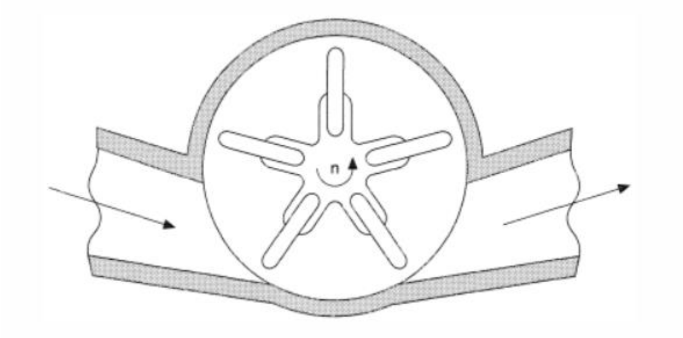
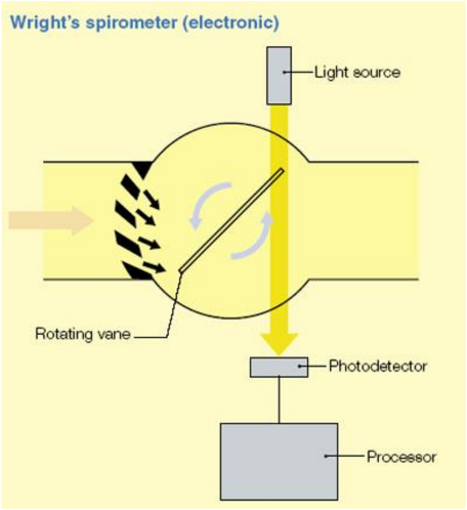
Volume count flowmeter : 1 rotating





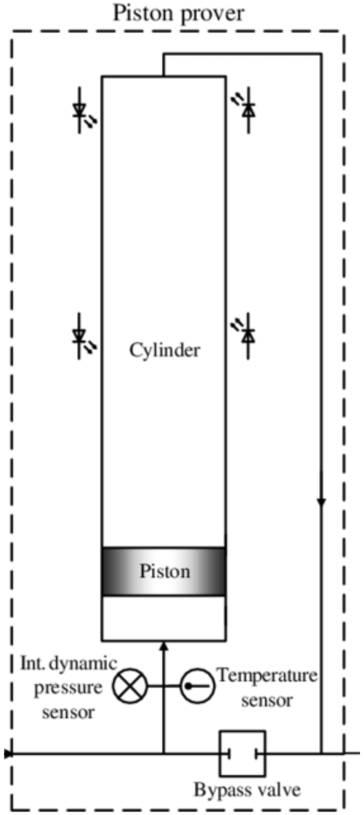




Rotation speed is related to volume flow :

- not very precise (leaks, flow regime sensitivity)

Volume count flowmeter : 2 linear



Volume discrete counting (V/δt is the volume flow)
Quite precise, used as calibration device

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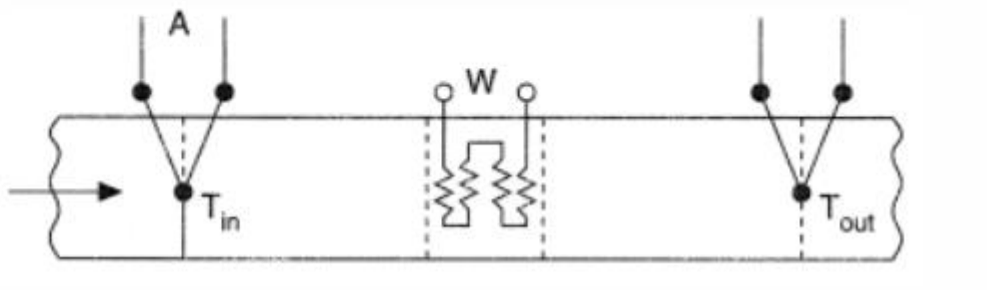
Thermal mass flowmeter



- Easy to use
- Composition of gas has to be known
- No traceability compared to other techniques (e.g. critical nozzles)

Need to be calibrated in order to provide traceability to SI units

No Europe NMI’s provide direct traceability to H2
➔ need a conversion factor
➔ very often calibrated with He

Known manufacturers

Bronkhorst® BROOKS® INSTRUMENT vögtlin instruments SENSIRION THE SENSOR COMPANY

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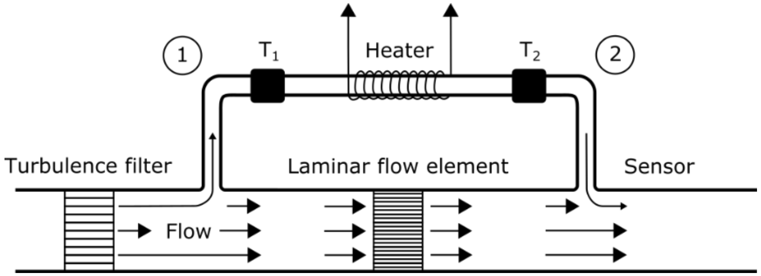
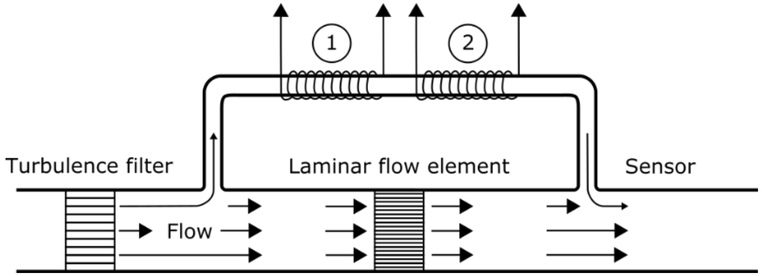
Thermal mass flowmeter

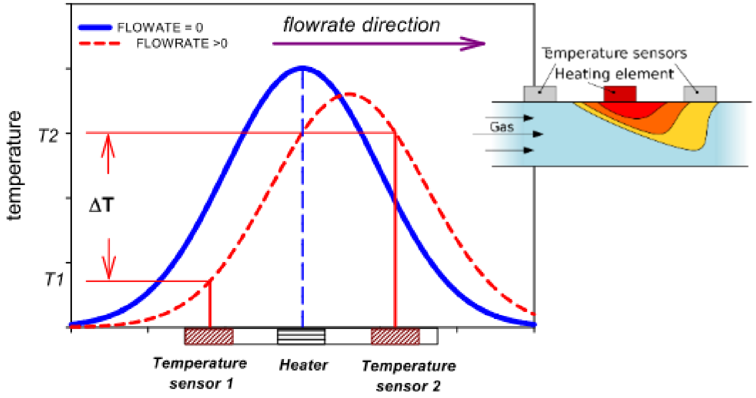
CTTMFs (Capillary Type Thermal Mass Flow Meters)

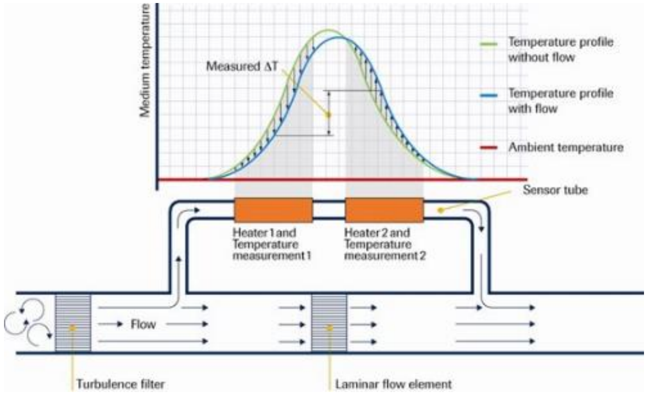
2 technologies

assumption $\frac{\dot{m}_{capillary}}{\dot{m}_{main\ tube}} = cst$









Temperature rise flowmeter

$$\dot{m} = \mathrm{cst}_{\mathrm{T}} . \Delta T$$

Rate loss heat flowmeter

maintaining $\Delta \mathrm{T} = cst$

increase rangeability

$$\dot{m} = \mathrm{cst}_{\mathrm{q}} . q$$

cst_q, cst_T depends on gas nature

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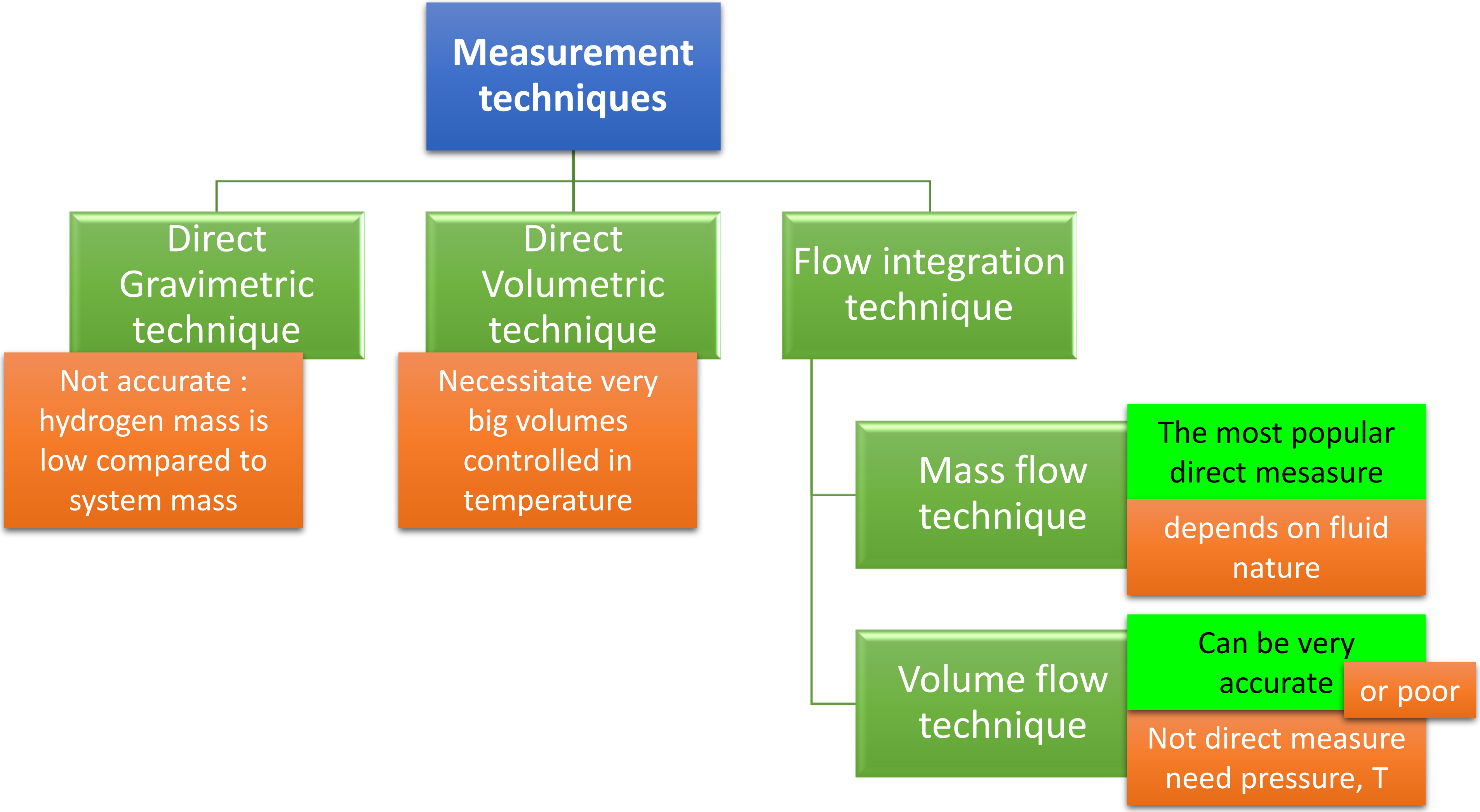
Measurement tech. – Integrated flow



Measurement techniques

Direct Gravimetric technique

Not accurate : hydrogen mass is low compared to system mass

Direct Volumetric technique

Necessitate very big volumes controlled in temperature

Flow integration technique

Mass flow technique

The most popular direct mesasure

depends on fluid nature

Volume flow technique

Can be very accurate

or poor

Not direct measure need pressure, T

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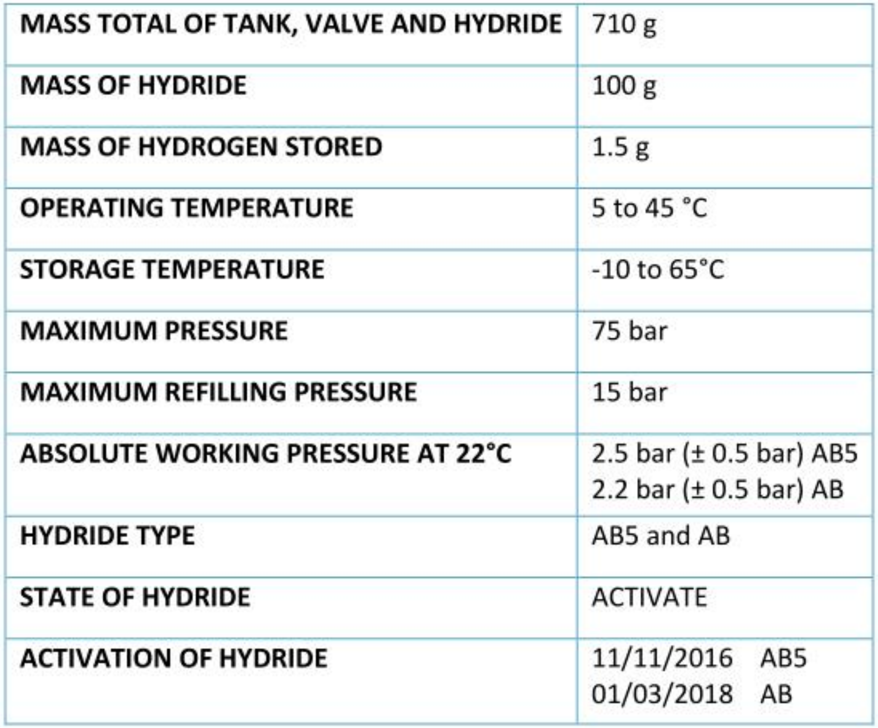
Test campaign on MAHYTEC hydride tank

The hydride tank characteristics



MASS TOTAL OF TANK, VALVE AND HYDRIDE	710 g
MASS OF HYDRIDE	100 g
MASS OF HYDROGEN STORED	1.5 g
OPERATING TEMPERATURE	5 to 45 °C
STORAGE TEMPERATURE	-10 to 65°C
MAXIMUM PRESSURE	75 bar
MAXIMUM REFILLING PRESSURE	15 bar
ABSOLUTE WORKING PRESSURE AT 22°C	2.5 bar (± 0.5 bar) AB5 2.2 bar (± 0.5 bar) AB
HYDRIDE TYPE	AB5 and AB
STATE OF HYDRIDE	ACTIVATE
ACTIVATION OF HYDRIDE	11/11/2016 AB5 01/03/2018 AB

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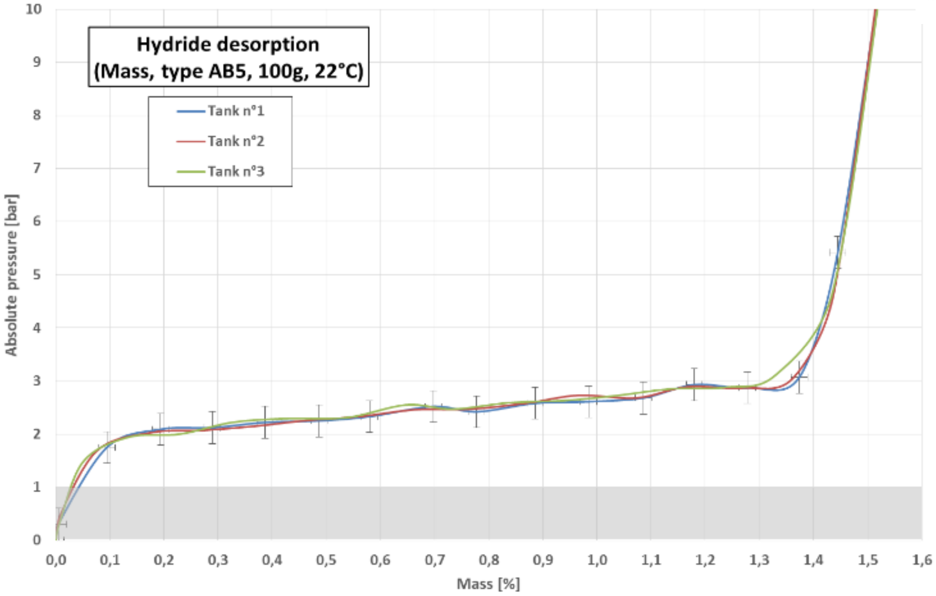
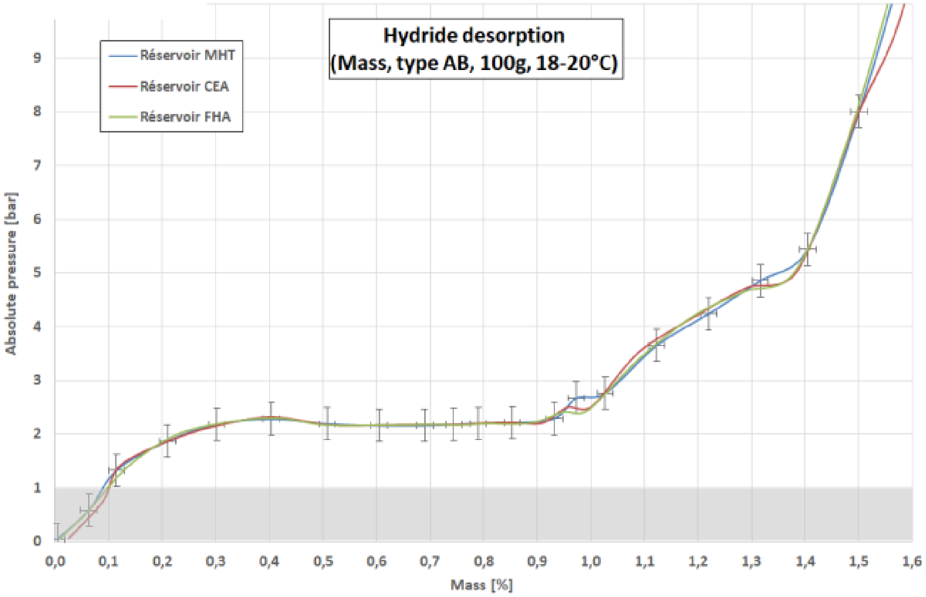
Test campaign on MAHYTEC hydride tank

The two hydrides tested

AB$_5$ type



AB type



Measured by the weight method

Characteristics of device:
Scale: max 750 g, e = 0.01 g, d = 0.001 g
Digital pressure gauge: EM: -1 … 30 bar, error: ± 0.2%

Condition test:
Loading: $P_{loading}$ = 10 bar and $T_{loading}$ = 22 °C
Unloading: $T_{Unloading}$ = 22 °C

Properties comparison

	H capacity	PCT	Activation	Impurity Effects	Cyclic Stability	Ease of manufacture	Pyrophoricity	Cost
AB$_5$	0	+	+	+	+	+	0	0
AB	0	+	-	-	-	+	+	+

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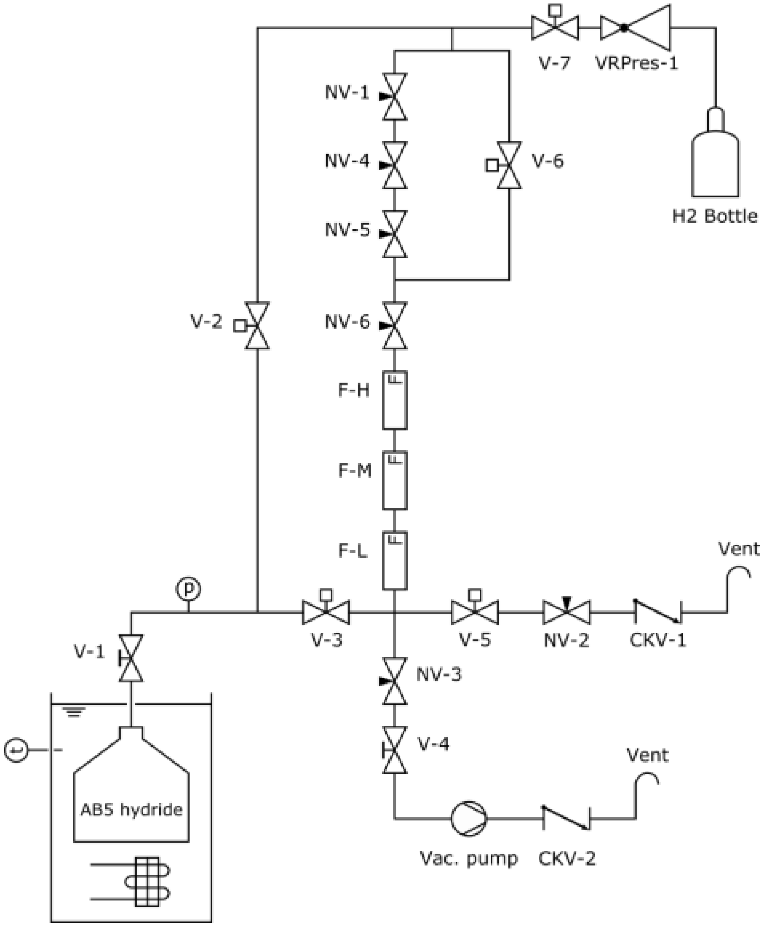
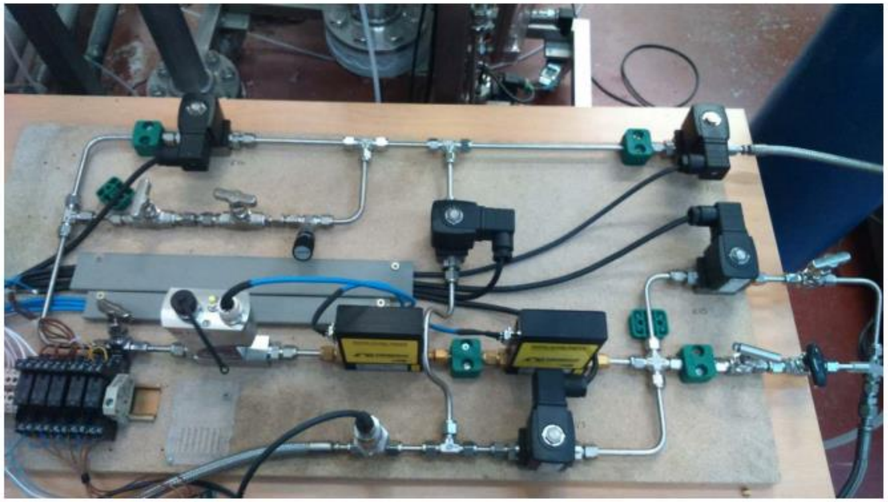
FHA installation

First installation for AB_5 test





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Advantage : 3 mass flow, larger range (but expensive)

Drawback : no mass flow control

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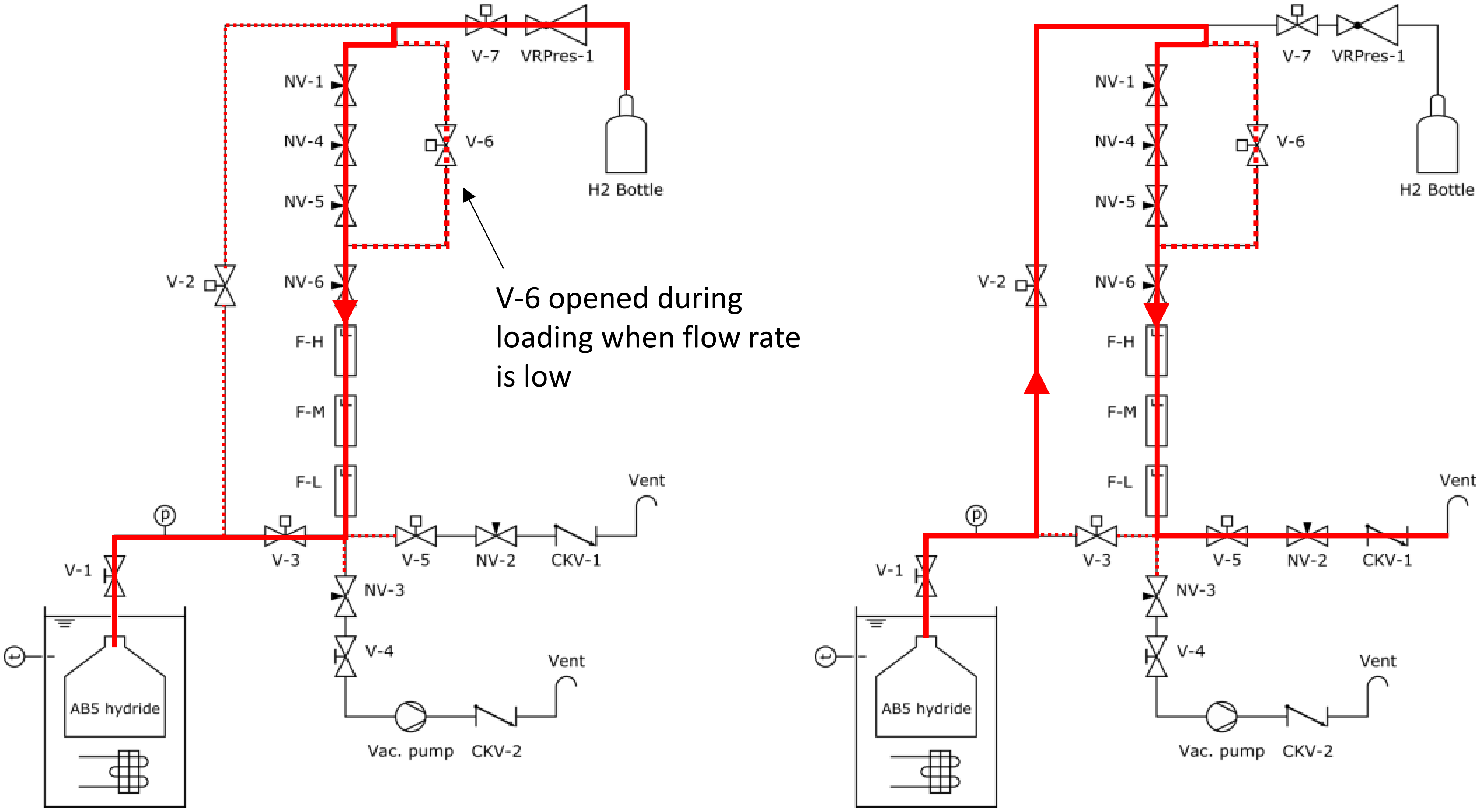
FHA installation

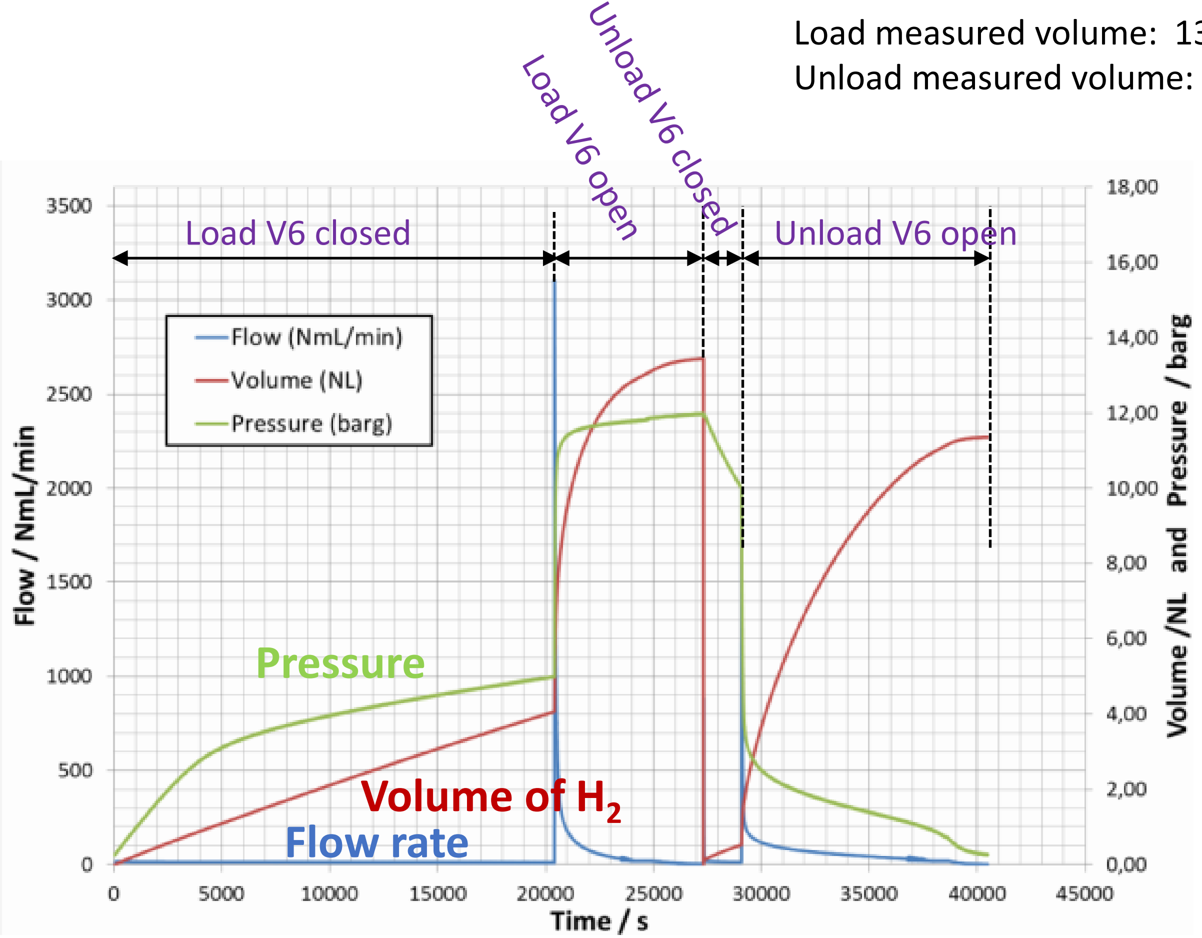


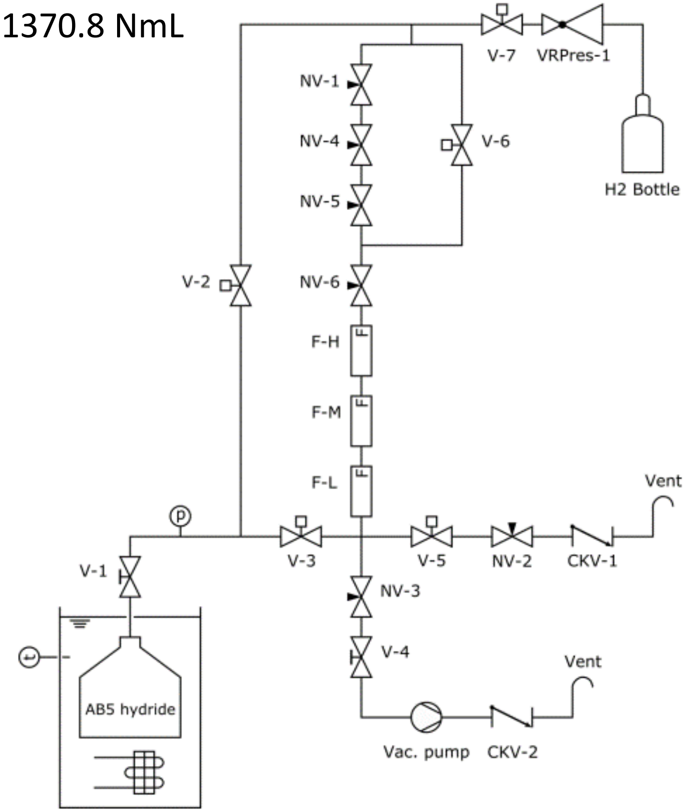
V-6 opened during loading when flow rate is low

FHA results – AB_5 tank

Examination of one test

Test conditions:
Temperature: 35 °C
Load V-6 opening: 5 barg
Unload V-6 opening: 11.9 barg
Flow to finish load: 1 NmL/min
Flow to finish unload: 1 NmL/min
Load measured volume: 13450.6 NmL
Unload measured volume: 11370.8 NmL





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FHA results – AB_5 tank

Pload=12 barg
Punload=0 barg

	Test no. 1	Test no. 2	Test no. 3	Test no. 4	Test no. 5	Test no. 6
Température (°C)	22	22	22	22	35	22
Load P V-6 opening (bar)	5	5	5	5	5	5
Unload P V-6 open (bar)	8	5.5	10	11.9	11.9	5.2
Load stop mass flow Nml/min	1	1	1	1	1	1
Unloas stop mass flow Nml/min	0.5	1	1	1	1	1
Volume (load) NmL	15214,9	15488	14947,6	15329,5	13450,6	15287,7
Volume (unload) NmL	11917,33	13491	13230,2	12312,2	11370,8	12123,8
Load/Unload Deviation %	+21.7	+12.9	+11.5	+19.7	+15.5	+20.7
Load MAHYTEC Deviation %	-9,44	-7,81	-11,03	-8,75	-19,94	-9,00
Unload MAHYTEC Deviation %	-29,06	-19,70	-21,25	-26,71	-32,32	-27,83
		NV-2, NV-4 NV-5 closed a bit				NV-2 closed

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FHA Results – 1st intallation on AB_5 tank

Conclusions

- ✓ High di-symmetry of load and unload measures
- ✓ Underestimation compare to the Mahytec capacity measure
  depending on the adjustments, from -7% to -30% difference
- ✓ Adjustement of needle valve opening is difficult (iterative)
- ✓ Despite the use of needlevalves, there are overflows at each stage
- ✓ Needle valves oblige to cut the load into two parts (V6 opening) with overflow at each V6 opening
  - ➔ 1 overflow at loading, 2 overflows at unloading

- ✓ Capacity measured is dependant on needle valves adjustements and switching pressure (for V-6 valve) !

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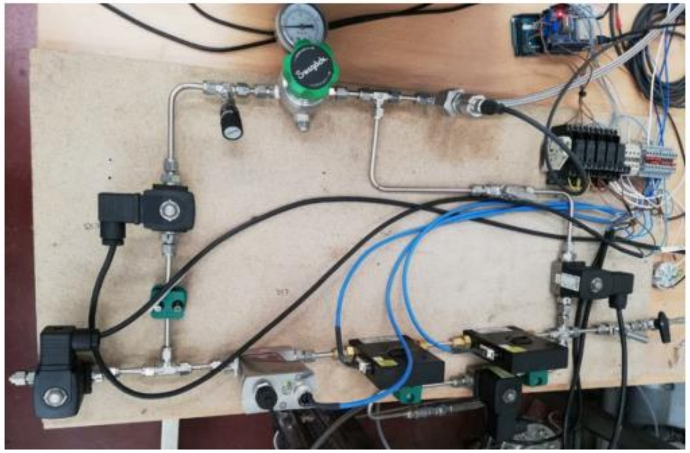
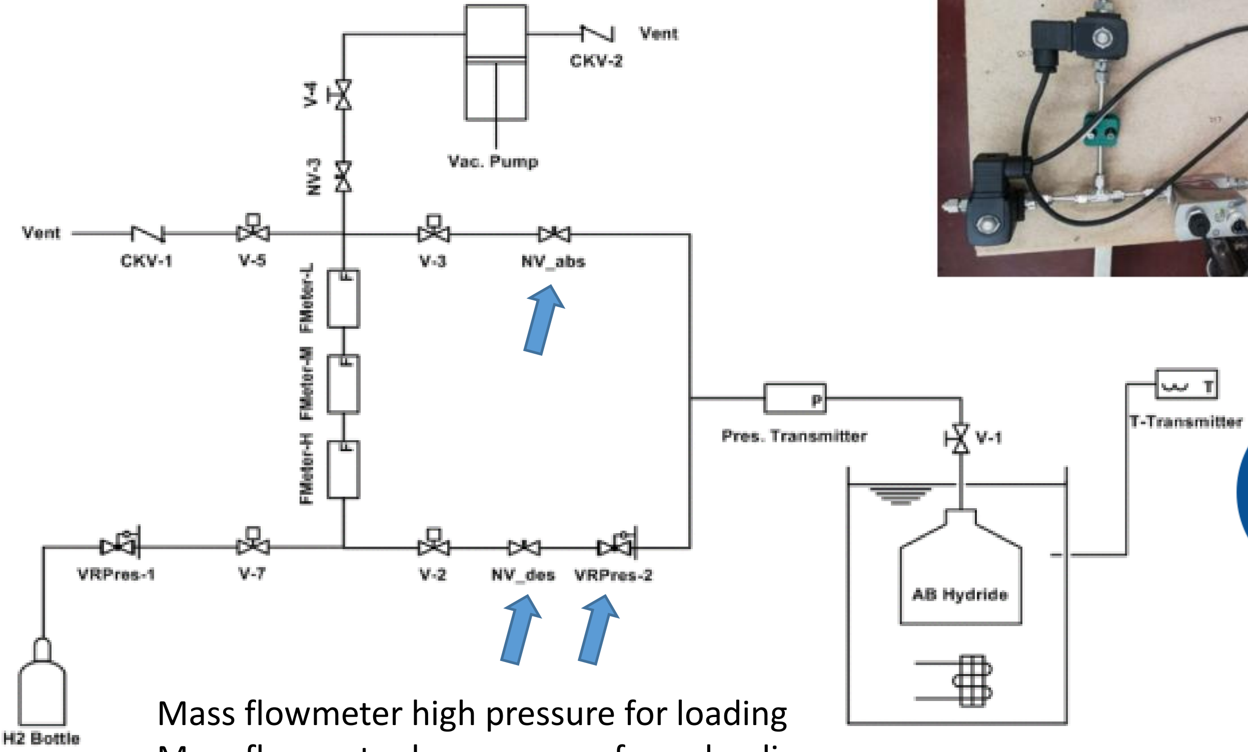
FHA 2cd installation

Second installation for AB test





Mass flowmeter high pressure for loading
Mass flowmeter low pressure for unloading

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EN ARAGÓN

New :

- Needle valve (NV_abs) after flowmeter in order to maintain P more constant on flowmeter
- Pressure regulator valve (VRPres-2) added for desorption before a needle valve (NV_des)

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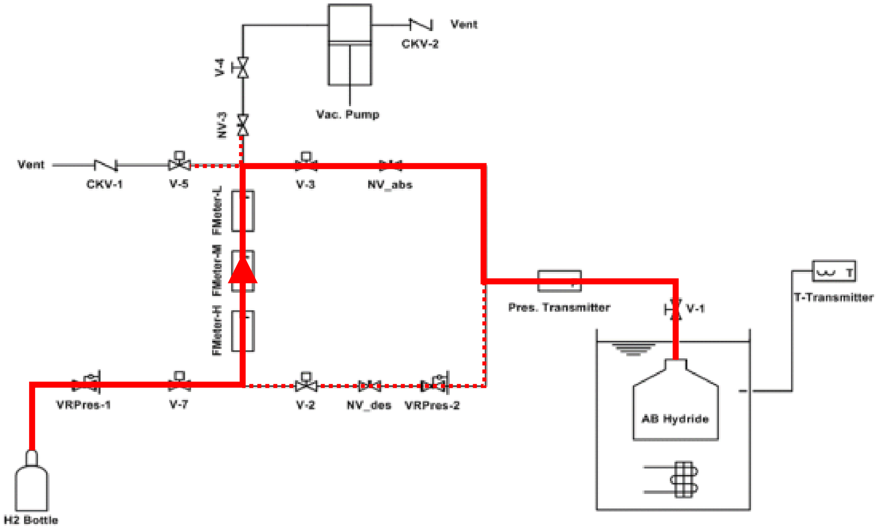
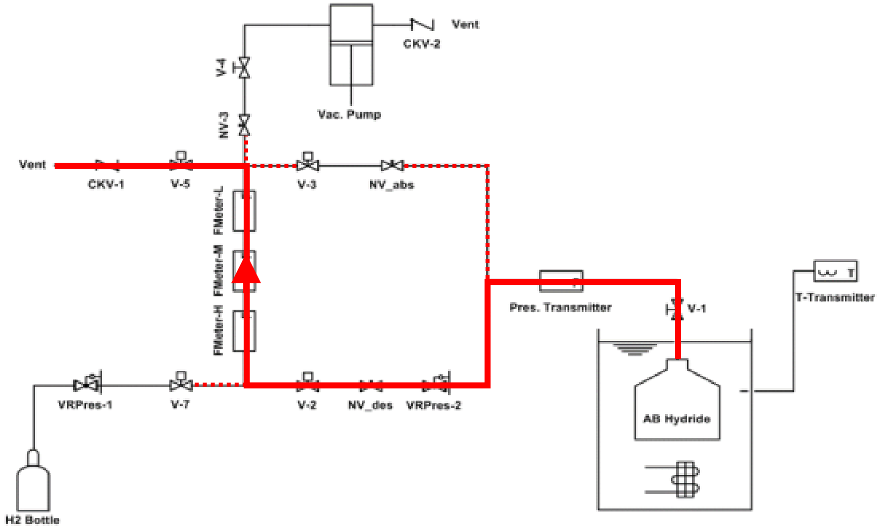
FHA 2cd installation

First installation for AB test





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FHA Results on AB tank

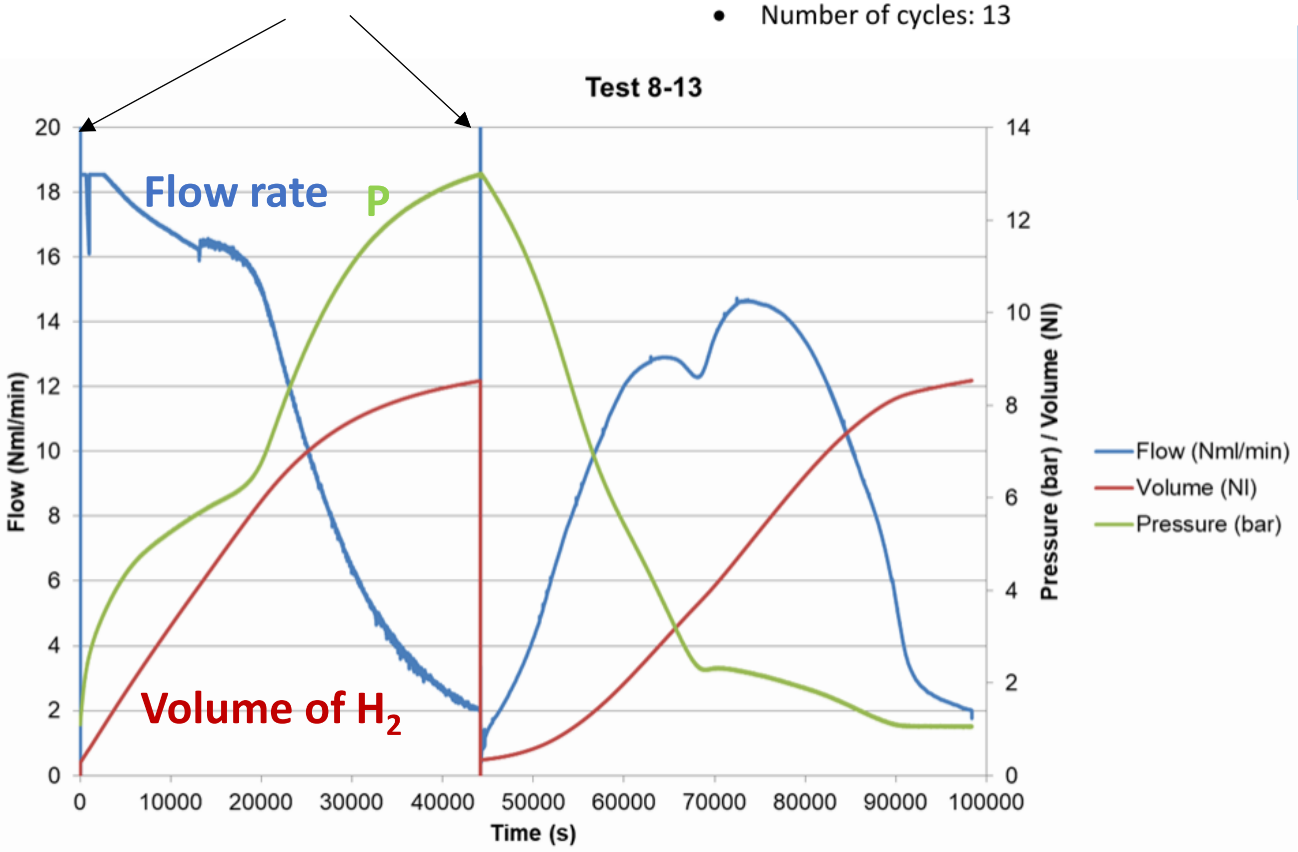
Examination of one test

The test was performed under the following conditions:

- Temperature: 22 °C
- Inlet Pressure: 14.5 barg (15.5 bara)
- Flow to finish load: 2 NmL/min
- Pressure defined to finish the load ≥ 11 barg (12 bara)
- Flow to finish unload: 2 NmL/min
- Pressure defined to finish the unload ≤ 0.1 barg (1.1 bara)
- Number of cycles: 13

Both the pressure and the flow criterions have to be accomplished

much shorter overflows



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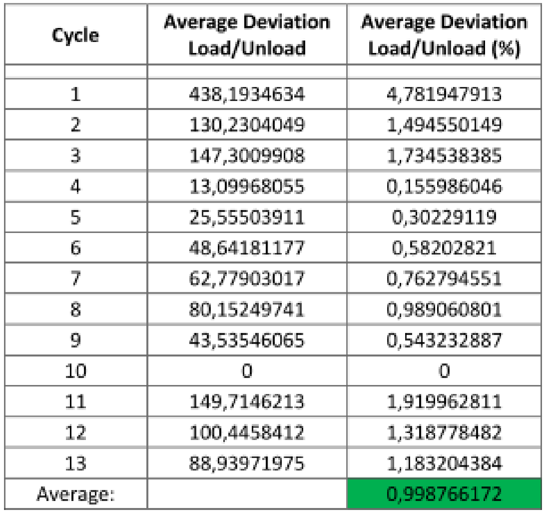
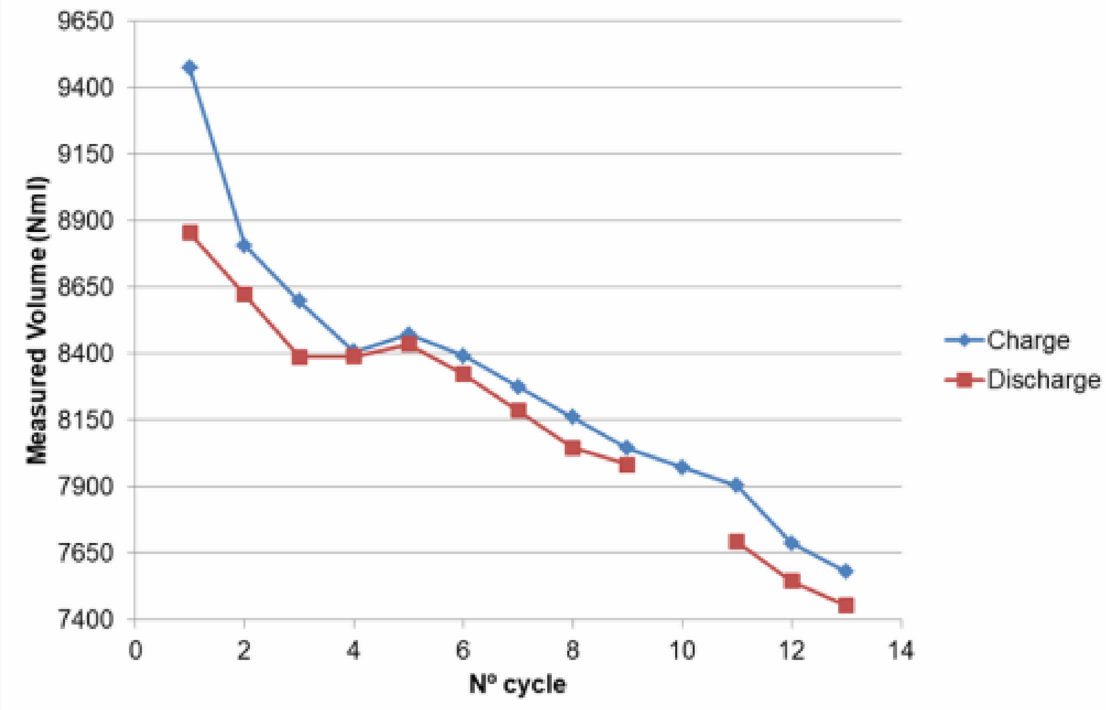
FHA Results – 2cd installation on AB tank

Results on 13 cycles



Cycle	Average Deviation Load/Unload	Average Deviation Load/Unload (%)
1	438,1934634	4,781947913
2	130,2304049	1,494550149
3	147,3009908	1,734538385
4	13,09968055	0,155986046
5	25,55503911	0,30229119
6	48,64181177	0,58202821
7	62,77903017	0,762794551
8	80,15249741	0,989060801
9	43,53546065	0,543232887
10	0	0
11	149,7146213	1,919962811
12	100,4458412	1,318778482
13	88,93971975	1,183204384
Average:		0,998766172



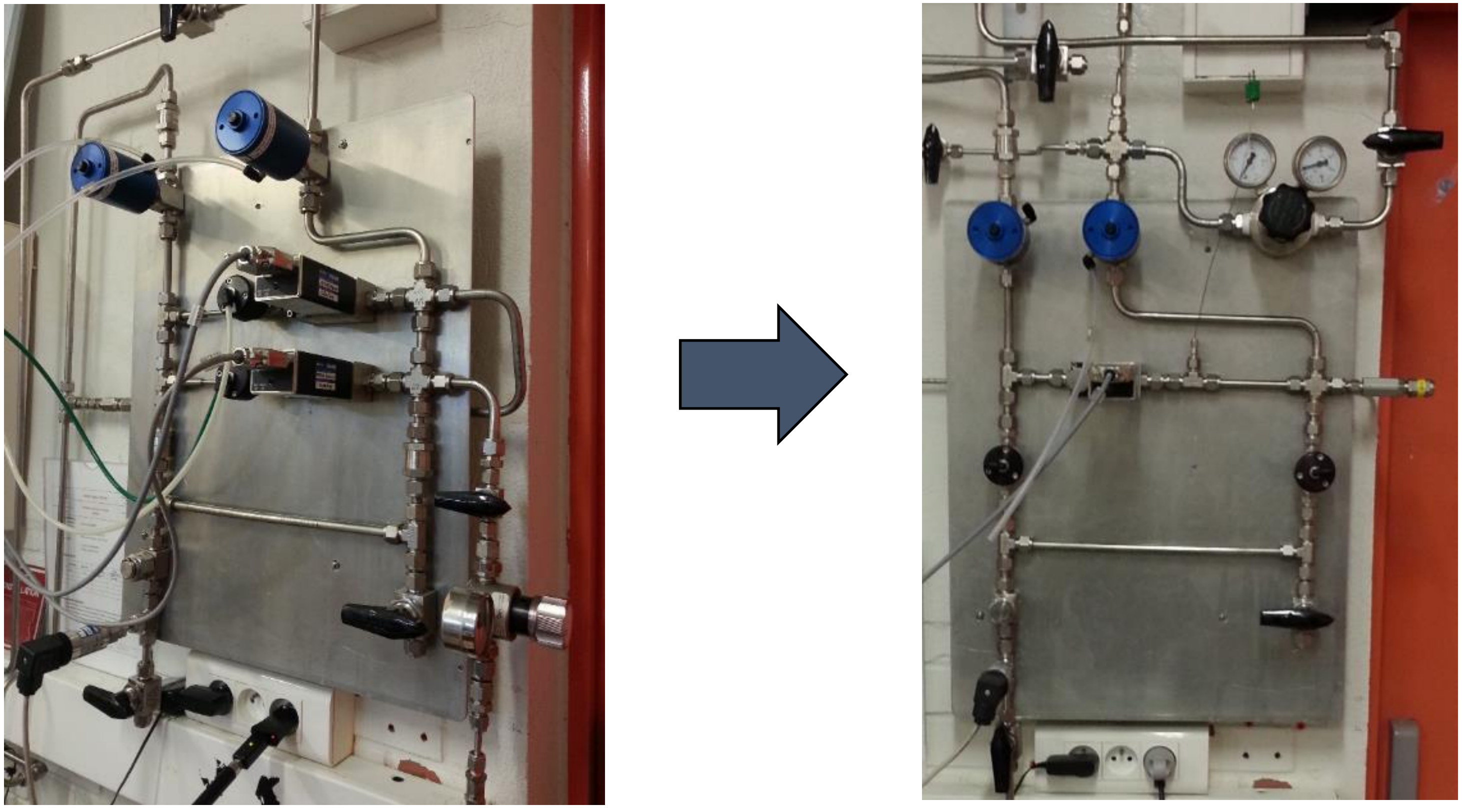
Much closer values for loading and unloading

Significant decrease of capacity : behavior of the AB hydride ? or a malfunctioning of pressure reducer VRPres-1

CEA installation

The test bench have been modified for the project :

- **remove the 2cd mass flow**
- **replace the check valve by simple valves**
- **introduce a length before the mass flow in order to have a better establishment length**
- **change the PRD to 15 bars**



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CEA installation

CySHY test bench

Gas panel

Thermoregulator

Water bath in which the hydrogen tank is installed

The 10 g/h mass flow has been re-calibrated to 800 Nml/min.

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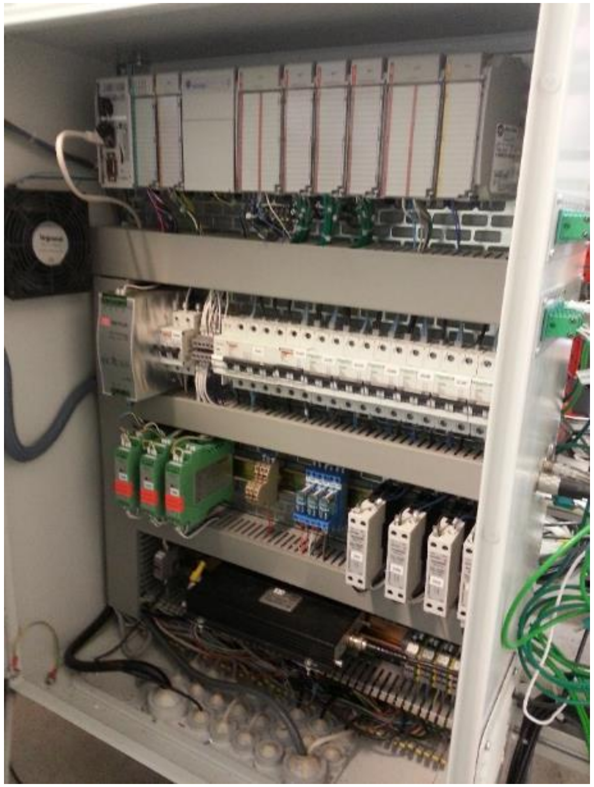
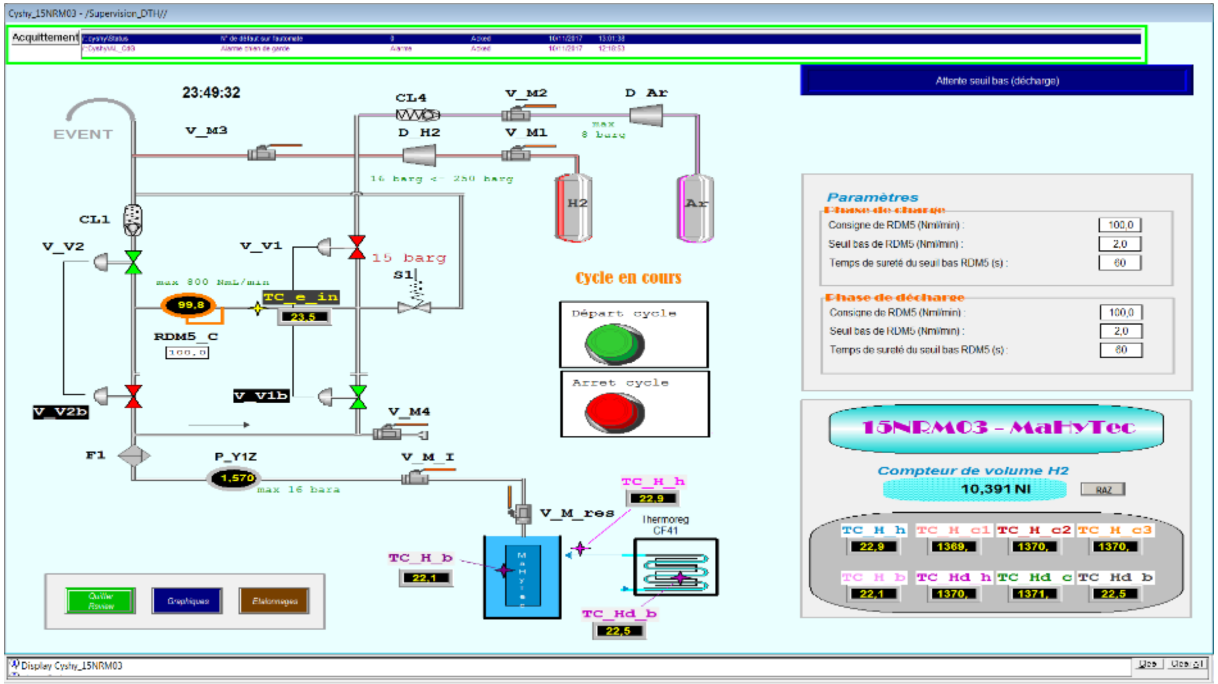
CEA installation

Programmable automaton (Allen Bradley)



Synoptic (RS-View)



Cyshy_15NRM03 - /Supervision_DTH//

Acquittement

::cyshy/Status	N° de défaut sur l'automate	0	Acked	10/11/2017	13:01:38
::CyshyVAL_CdG	Alarme chien de garde	Alarme	Acked	10/11/2017	12:18:53

Attente seuil bas (décharge)

Paramètres

Phase de charge

Consigne de RDM5 (Nml/min) : 100,0

Seuil bas de RDM5 (Nml/min) : 2,0

Temps de sureté du seuil bas RDM5 (s) : 60

Phase de décharge

Consigne de RDM5 (Nml/min) : 100,0

Seuil bas de RDM5 (Nml/min) : 2,0

Temps de sureté du seuil bas RDM5 (s) : 60

15NRM03 - MaHyTec

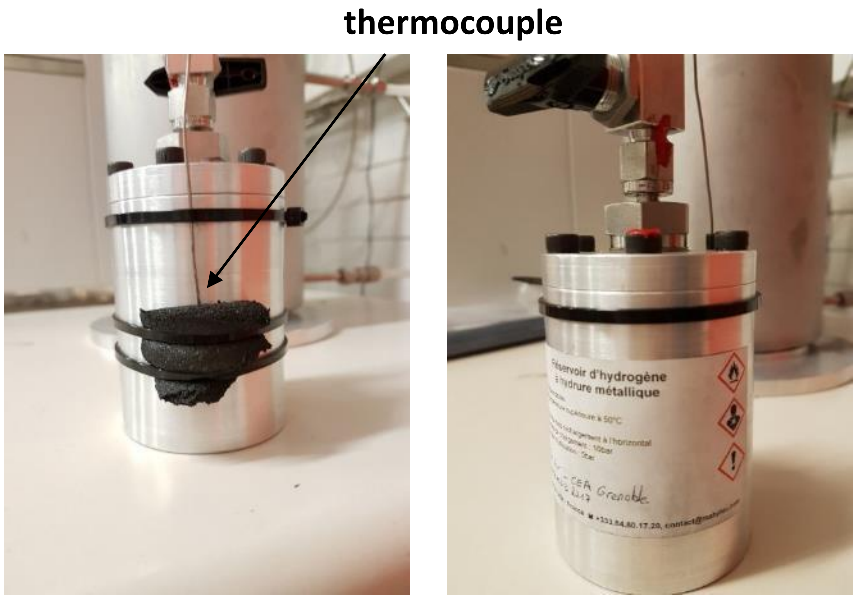
Compteur de volume H2: 10,391 Nl

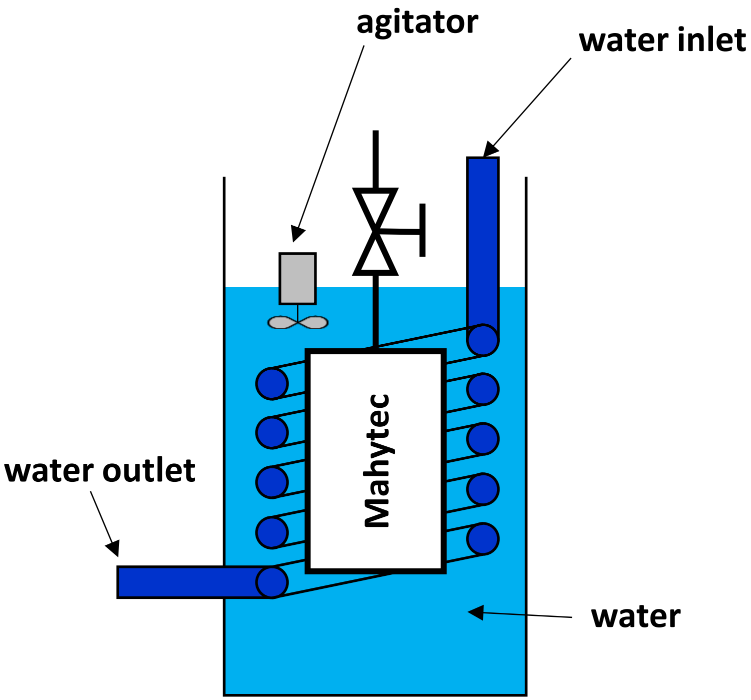
TC_H_h	TC_H_c1	TC_H_c2	TC_H_c3
22,9	1369,	1370,	1370,

TC_H_b	TC_Hd_h	TC_Hd_c	TC_Hd_b
22,1	1370,	1371,	22,5

Display Cyshy_15NRM03

CEA installation





EMPIR EURAMET
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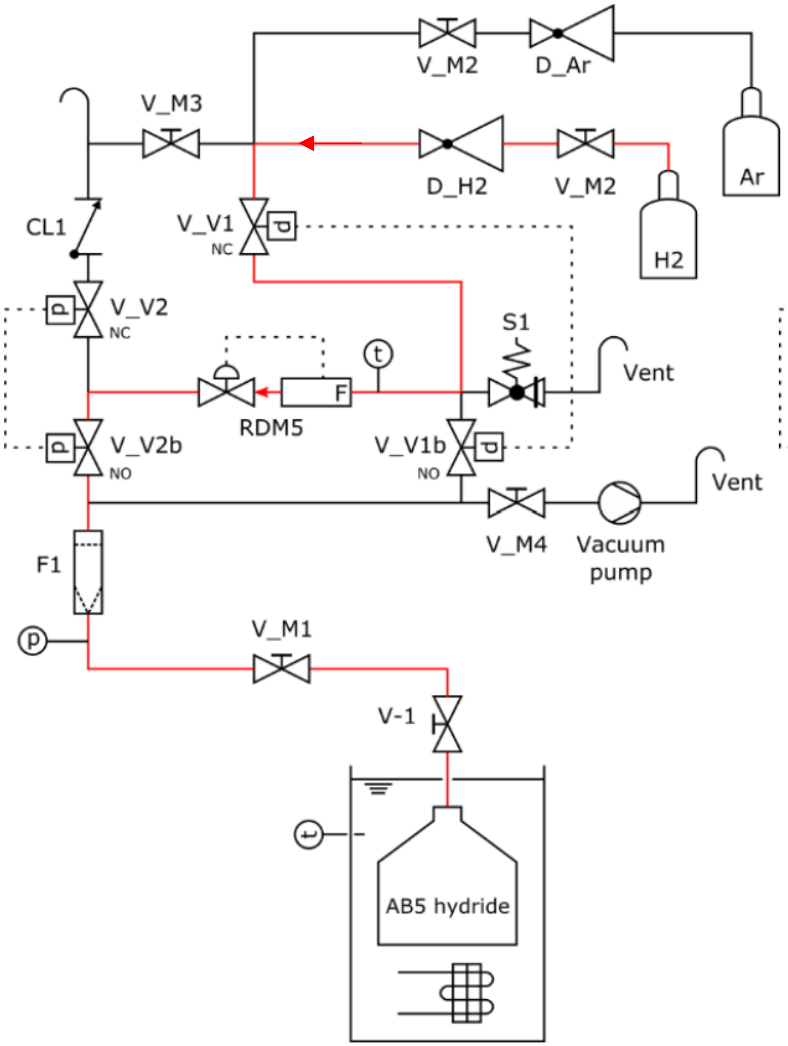
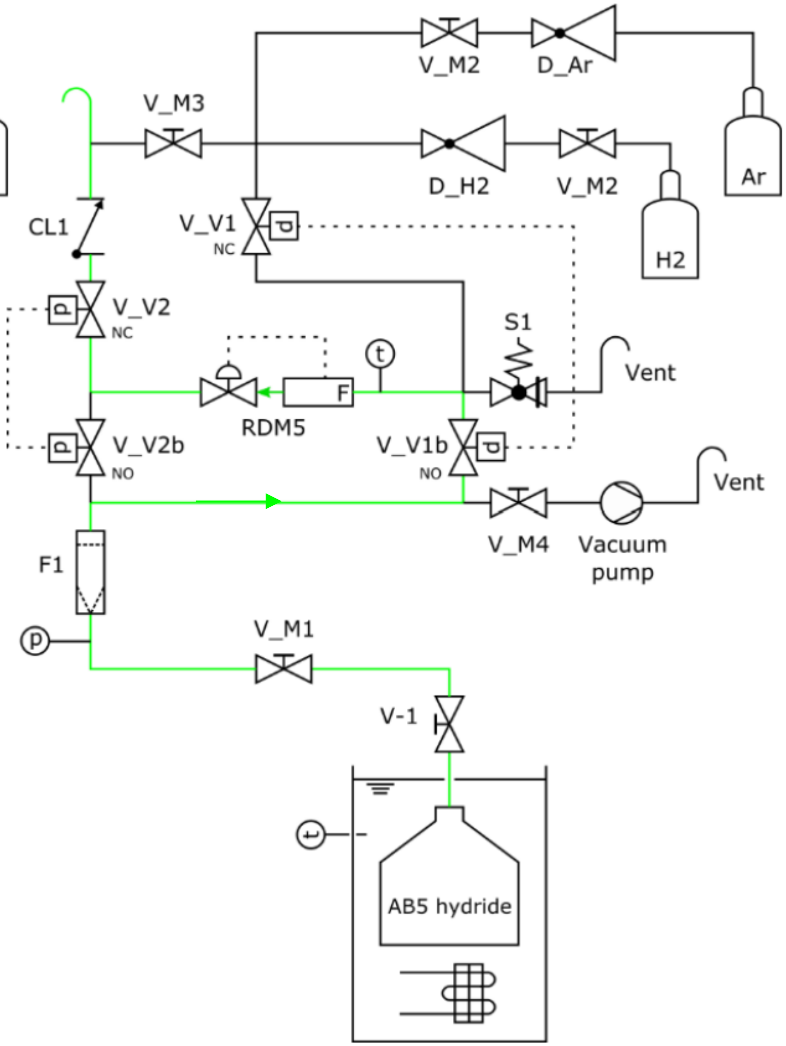
CEA installation

Loading

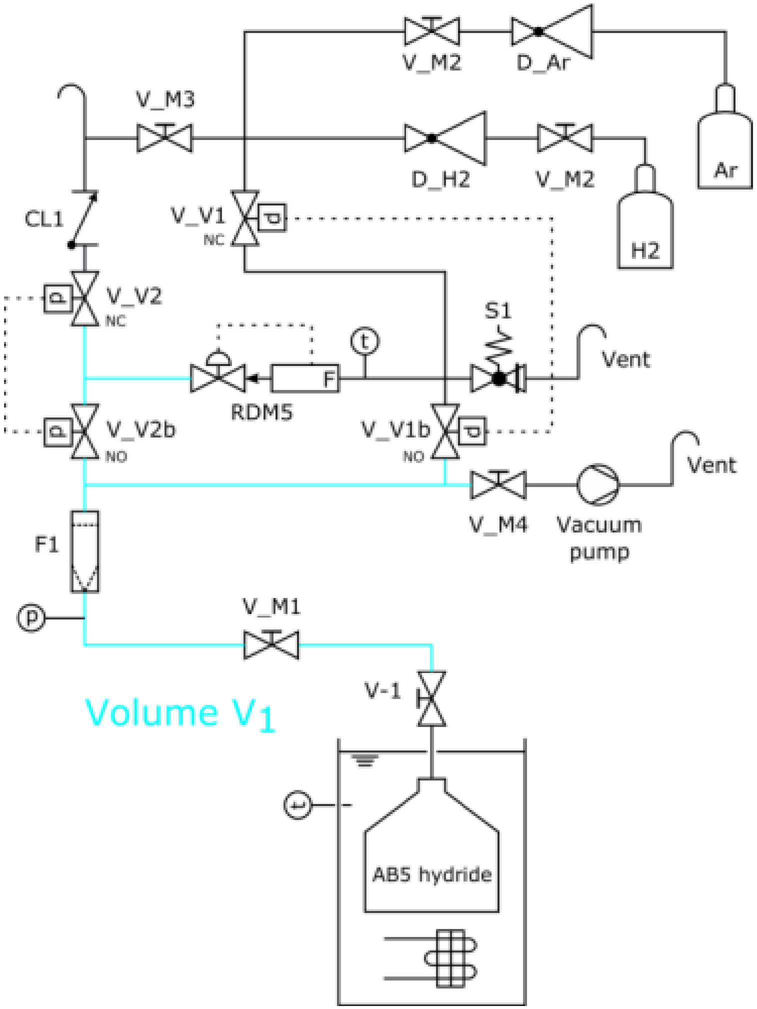


Unloading



CEA installation

Dead volume correction



V1 volume is counted by mass flowmeter but is not entering in the tank
➔ has to be withdrawn from measure

CEA installation

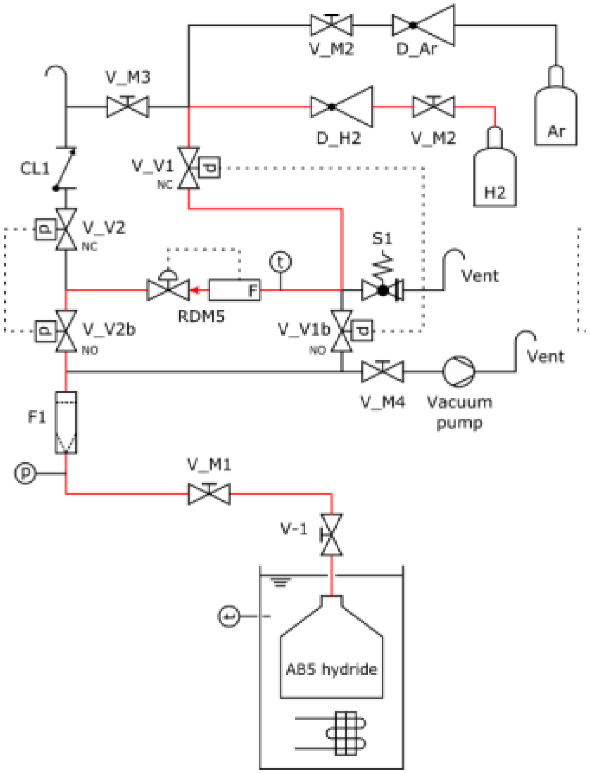
Test protocol

Initial conditions

P réservoir	-1	barg
T réservoir	22	°C
P H2 source	12.135	barg

Adjustable parameters

RDM5 load	RDM5_load	400	Nml/min
RDM5 déload	RDM5_unload	400	Nml/min
Threshold for mass flow too low	SB_RDM5	2	Nml/min
Stability time	SB_tempo	60	s



Load	1	RDM5_C (RDM5 set point) = 0	
	2	Open V_V1	
	3	RDM5_C = 0,1	in order to avoid overflow
	4	Wait : 5 s	
	5	RDM5_C = RDM5_load	
	6	Wait : 60 s	
	7	Close V_V1 when RDM5 < SB_RDM5 during more than SB_tempo	
	8	RDM5_C = 0	
Unload	9	Wait : 60 s	
	10	Ouverture V_V2	
	11	RDM5_C = 0,1	in order to avoid overflow
	12	Wait : 5 s	
	13	RDM5_C = RDM5_unload	
	14	Wait : 60 s	
	15	Close V_V2 when RDM5 < SB_RDM5 during more than SB_tempo	
	16	RDM5_C = 0	
	17	Wait : 60 s	
	18	Back to step 2	

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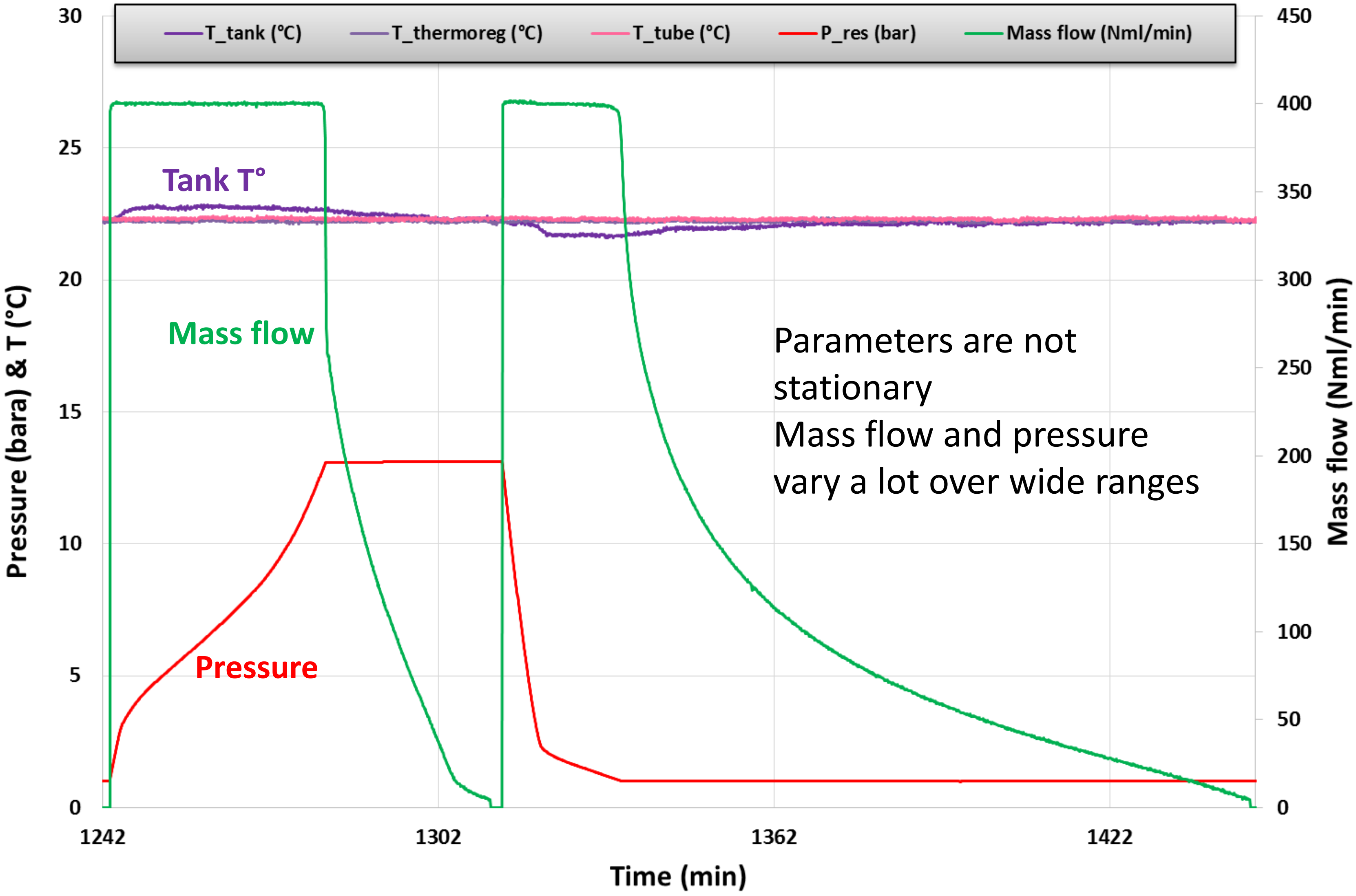
CEA Results – AB_5 tank

Experiment at 400 Nml/min : 5th cycle



Parameters are not stationary

Mass flow and pressure vary a lot over wide ranges

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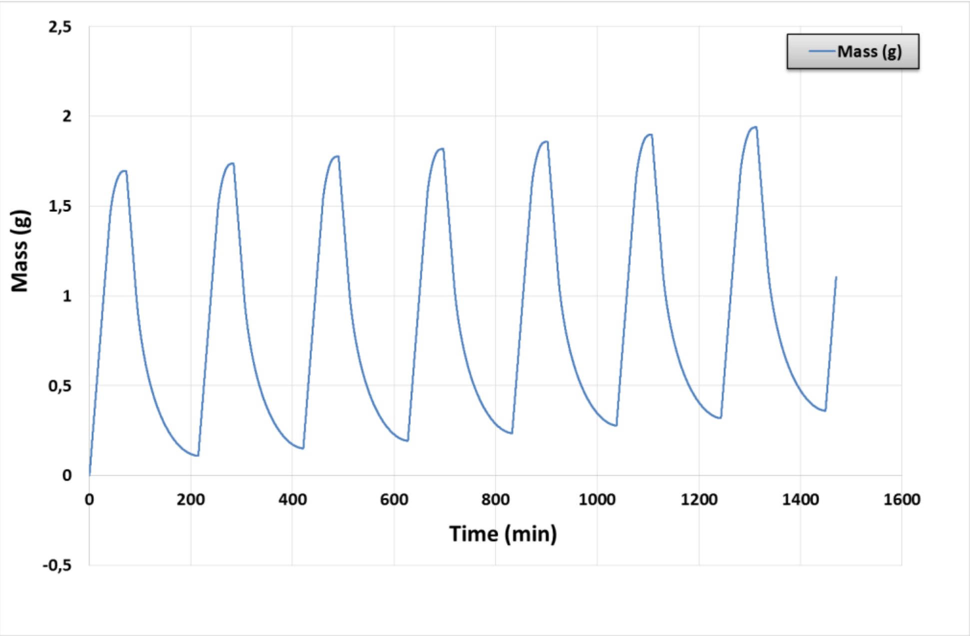
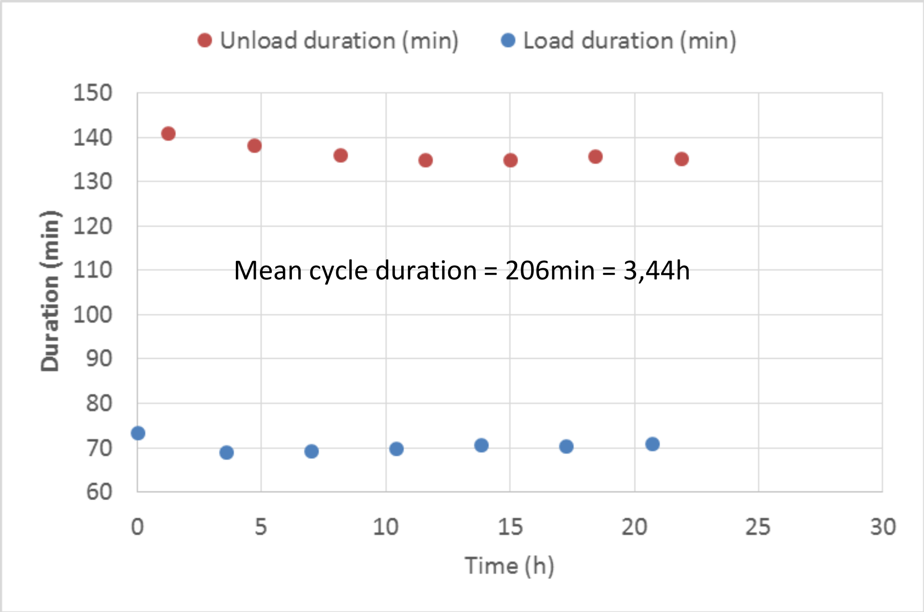
CEA Results – AB$_5$ tank

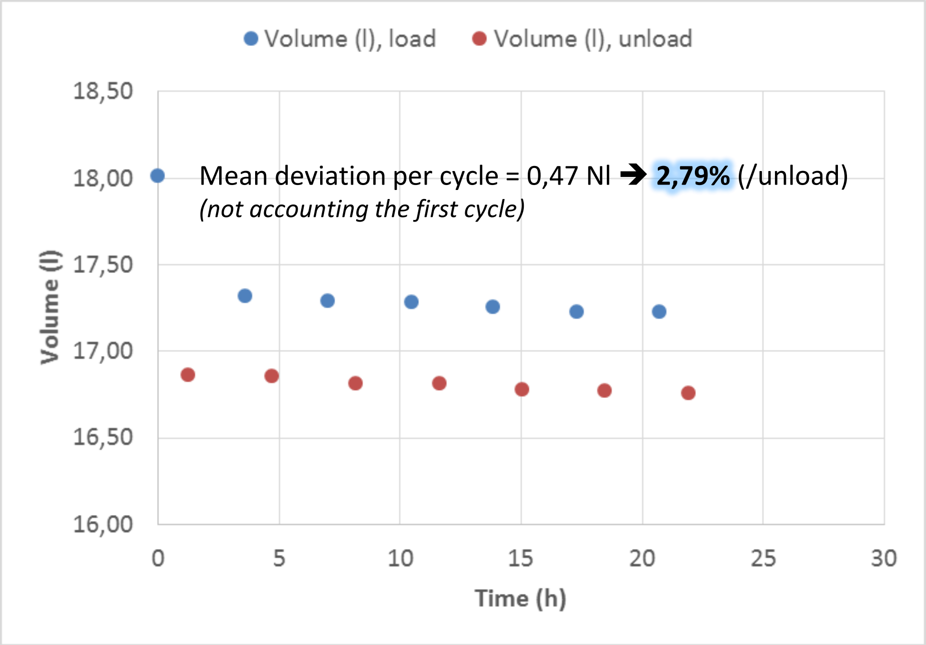
Experiment at 400 Nml/h

Cumulated mass



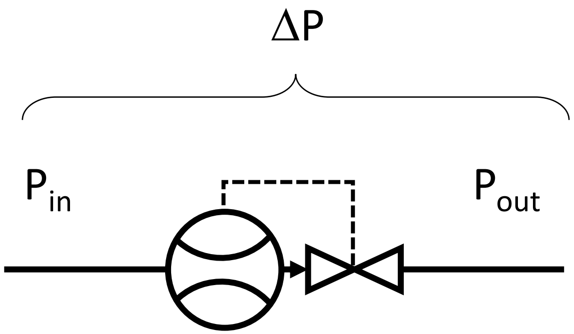


Mean cycle duration = 206min = 3,44h



Mean deviation per cycle = 0,47 Nl → **2,79%** (/unload)
(not accounting the first cycle)

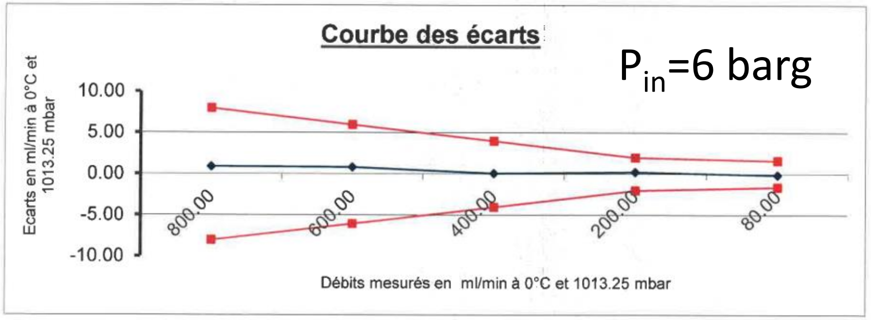
CEA Results

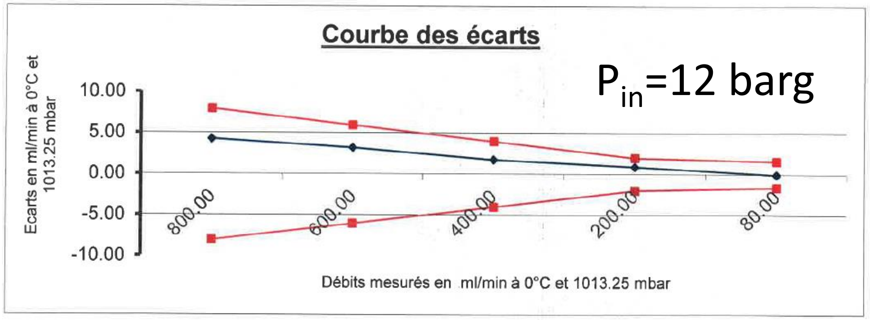


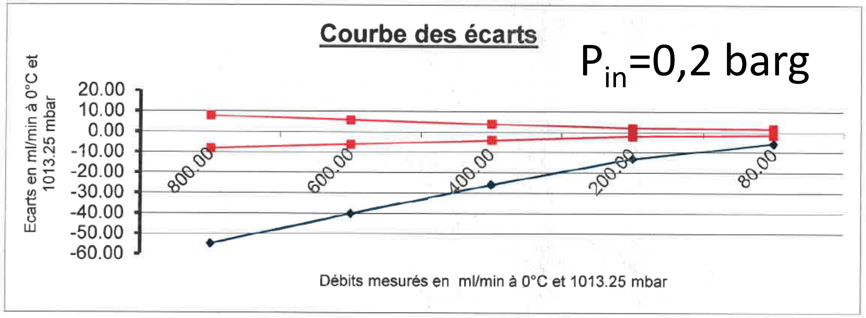
	P_{in} (bara)	P_{out} (bara)
Loading	13,136	P_{tank}
Unloading	P_{tank}	0,985

Problem when P or ∆P≈0 !!! ➔

Calibration as proposed by the provider







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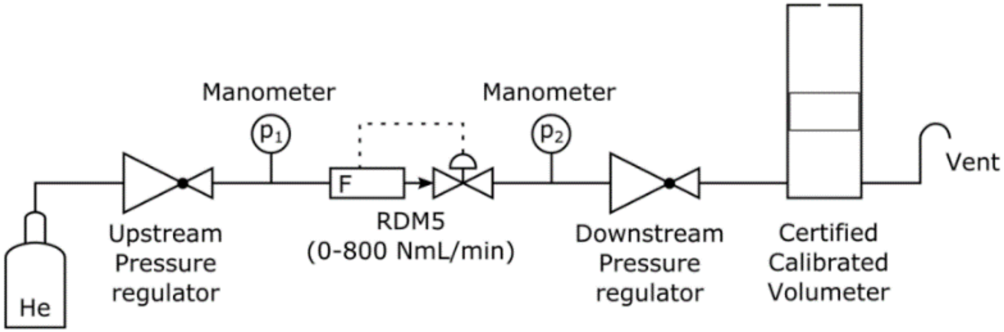
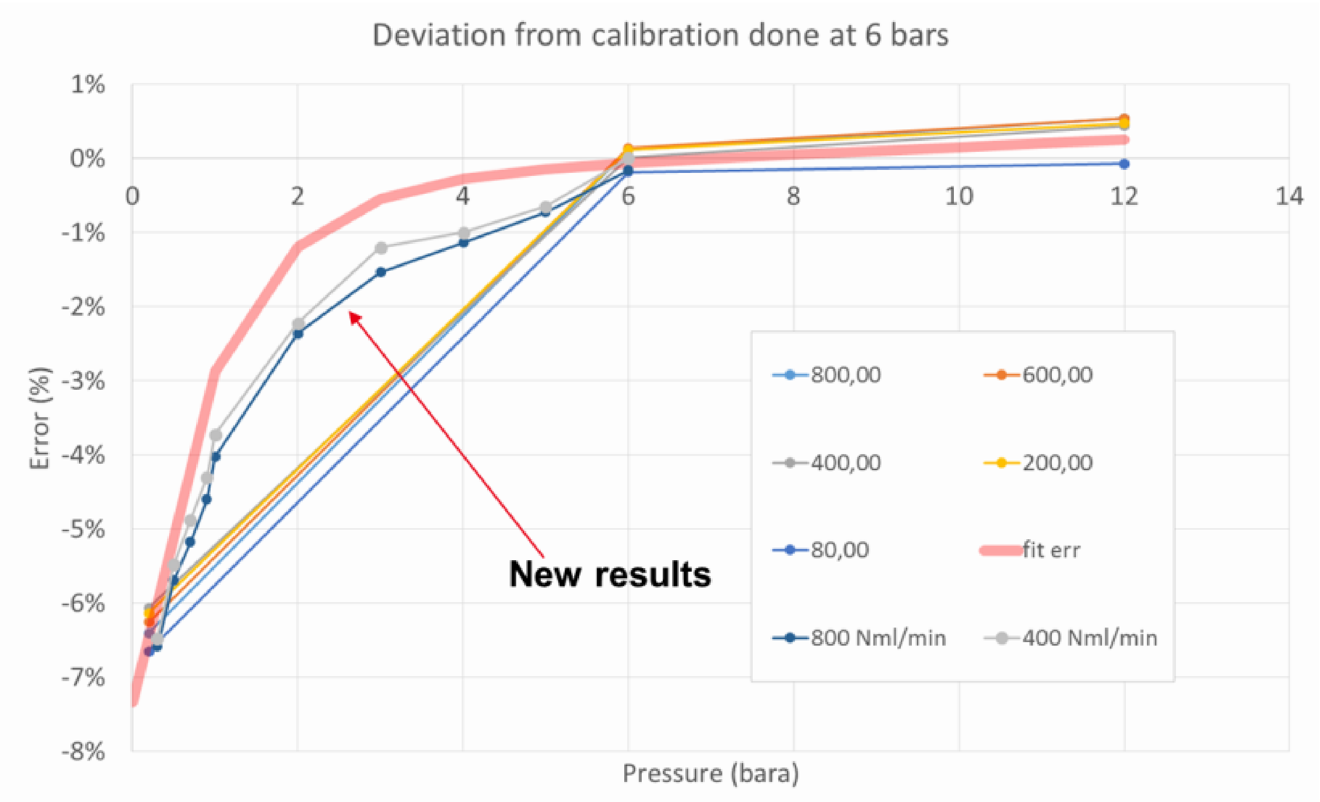
CEA Results

Result of extended calibration





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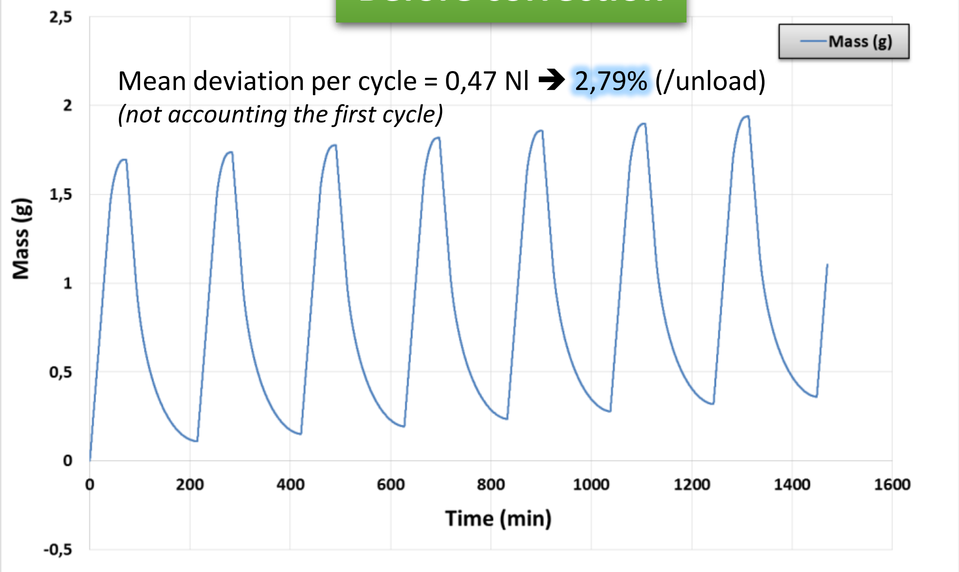
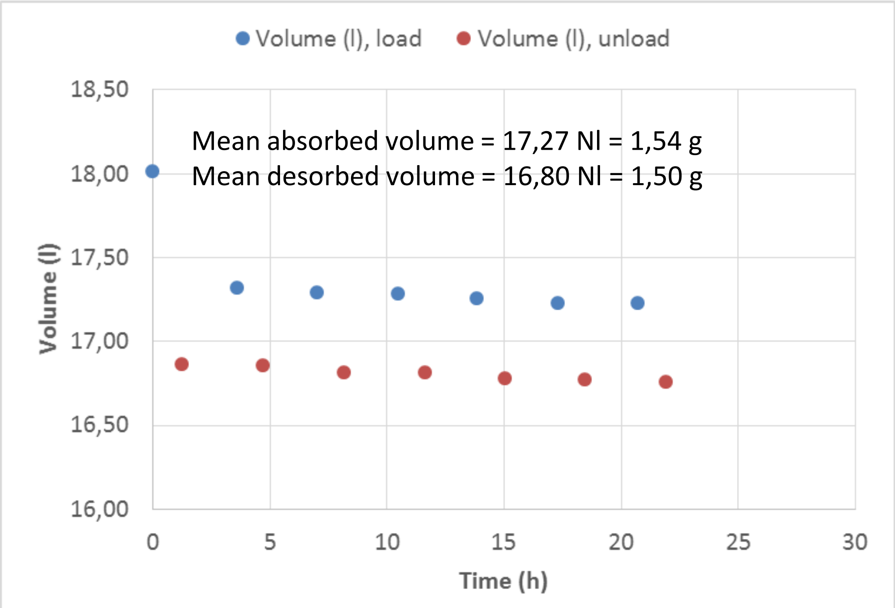
CEA Results – Correction

Result of extended calibration

Before correction

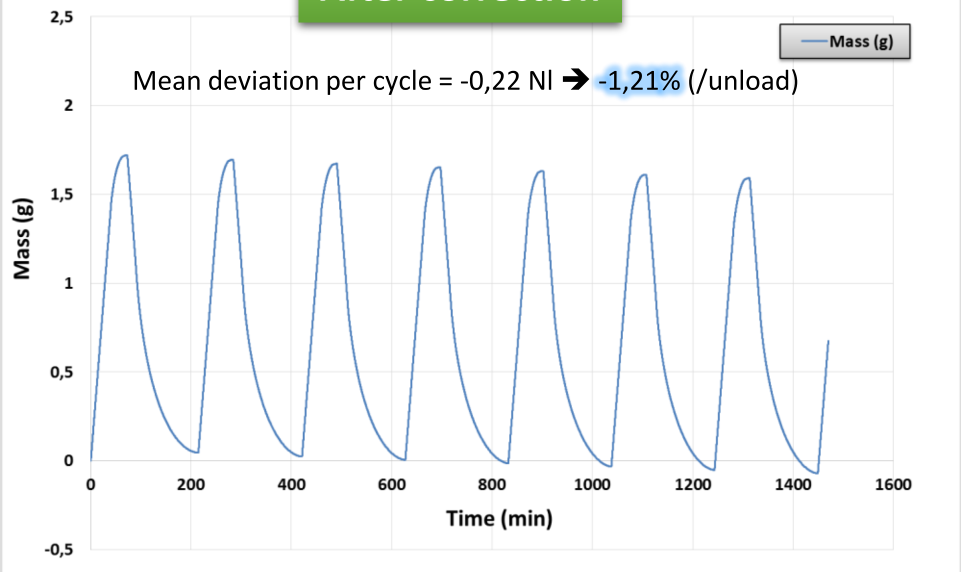


Mean deviation per cycle = 0,47 Nl ➔ 2,79% (/unload)
(not accounting the first cycle)

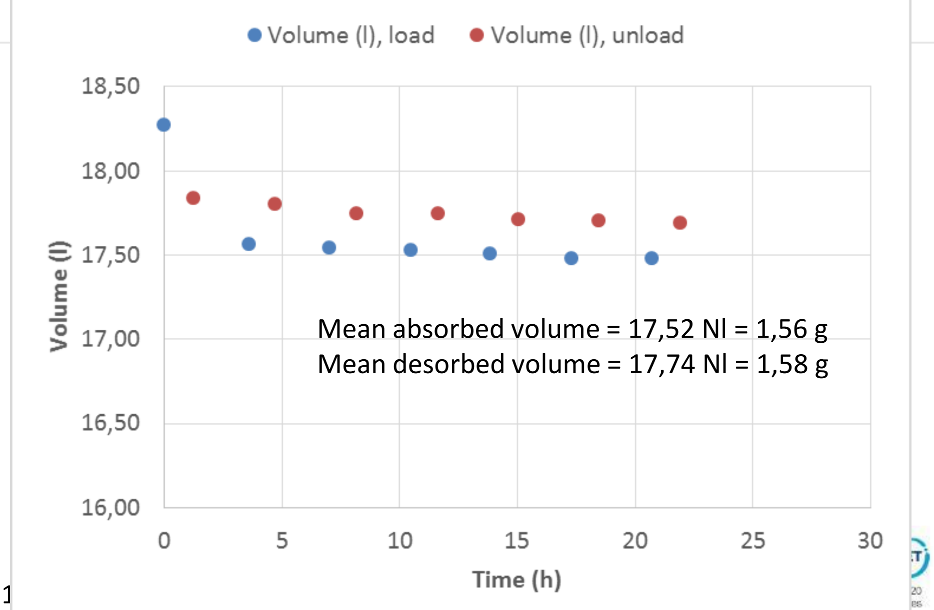


Mean absorbed volume = 17,27 Nl = 1,54 g
Mean desorbed volume = 16,80 Nl = 1,50 g

After correction

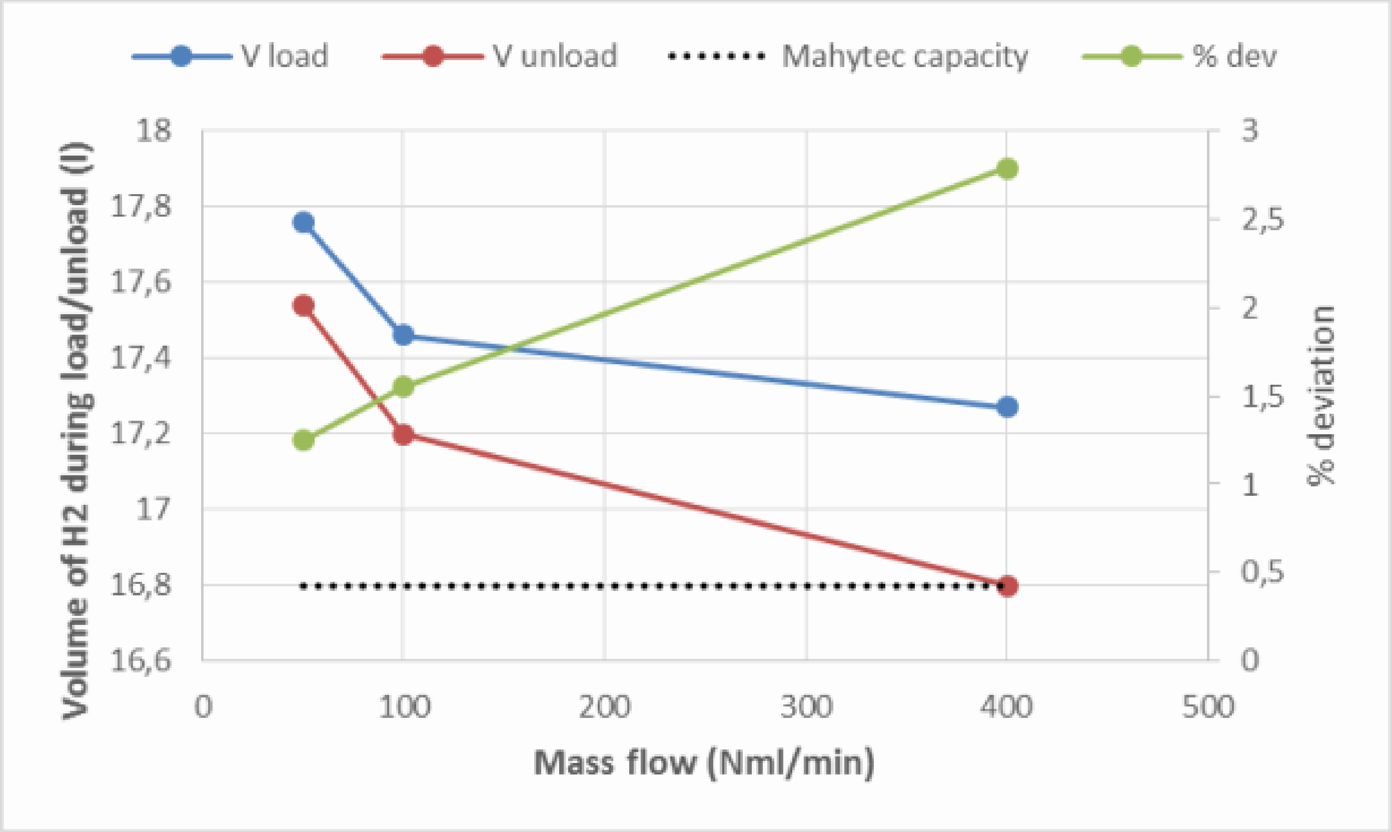


Mean deviation per cycle = -0,22 Nl ➔ -1,21% (/unload)



Mean absorbed volume = 17,52 Nl = 1,56 g
Mean desorbed volume = 17,74 Nl = 1,58 g

CEA Results



Not too bad compared to Mahytec measurement [0% : 5,7%]

Mass flow	t load	t unload	V load	V unload	Deviation	MAHYTEC capacity	Difference to announced capacity (load)	Difference to announced capacity (unload)
NmL/min	min	min	NL	NL		NL		
50	379.71	389.59	17.76	17.54	1.25%	16.80	5.71%	4.40%
100	193.17	219.27	17.46	17.20	1.55%	16.80	3.93%	2.38%
400	69.92	136.46	17.27	16.80	2.79%	16.80	2.80%	0.00%

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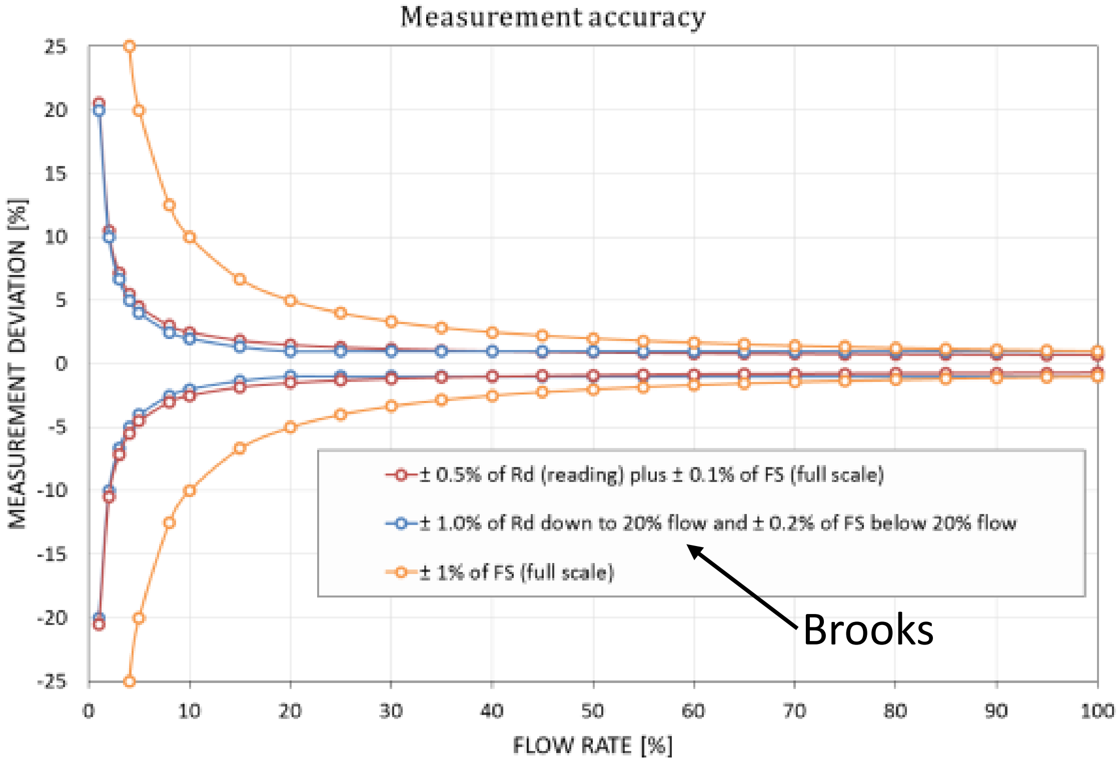
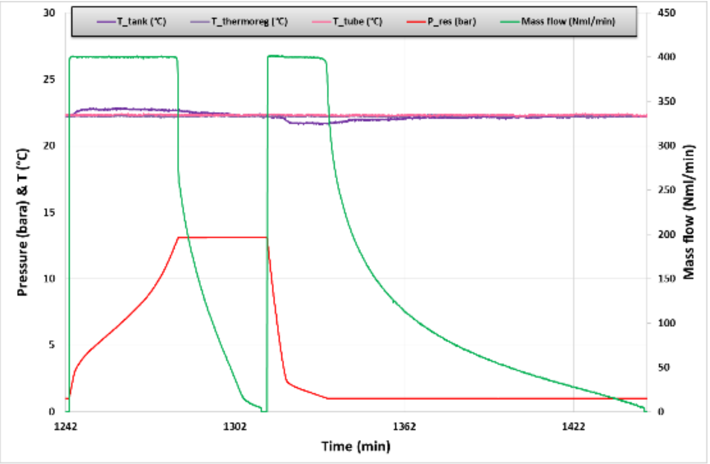
CEA Results

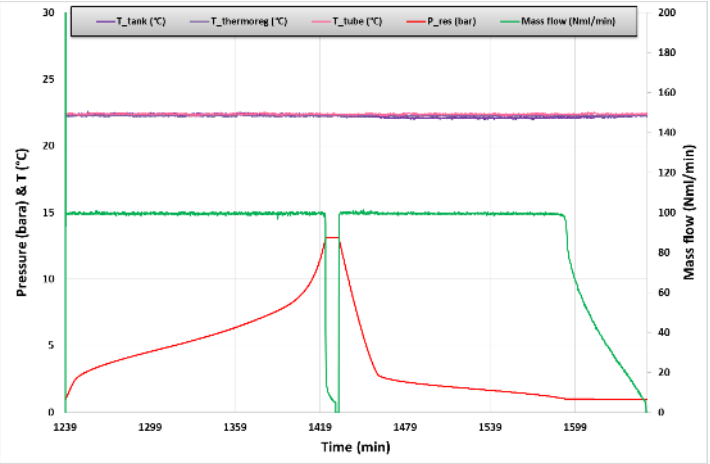


Brooks

quite di-symmetric loading unloading at 400 Nml/min



less di-symmetric loading unloading at 100 Nml/min



➔ can also explain the difference of capacity measured between loading and unloading

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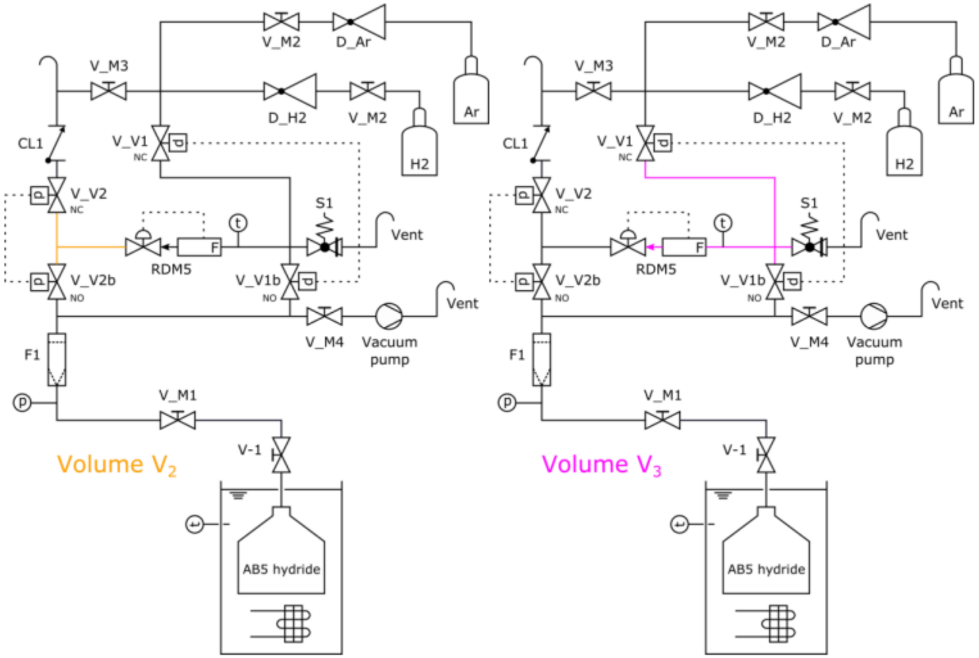
CEA - Further investigations

- ➢ Find origin of mass flow measure deviation at low P !?!?
  - ✓ Temperature bias via massflow meter body heating ? (control valve heating ?)
  - ✓ Flow regime change ?
  - ✓ Influence of flow rate piloting valve ? (transcient flows…)

- ➢ Do finer corrections
  - ✓ Volume V2 and V3
  - ✓ Di-symmetric loading/unloading
  - ✓ Sometimes : overflow
    - ➔ estimate error
  - ✓ Transcient flow regimes :
    - ➔ well time integrated ?



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2 points to pay attention

- When using needle valves (NV) for regulating the mass flows

  Mass flow vary a lot !!!

  ➔ reduce this : use pressure regulators in order to pilot constat ΔP on NV

- When using a mass flow meter controller (no NV)

  Use a controlled flow rate well in the mass flowmeter range

  Deviation when used at low pressure !

  ➔ avoid this : work near the calibration pressure
  or calibrate at two pressures

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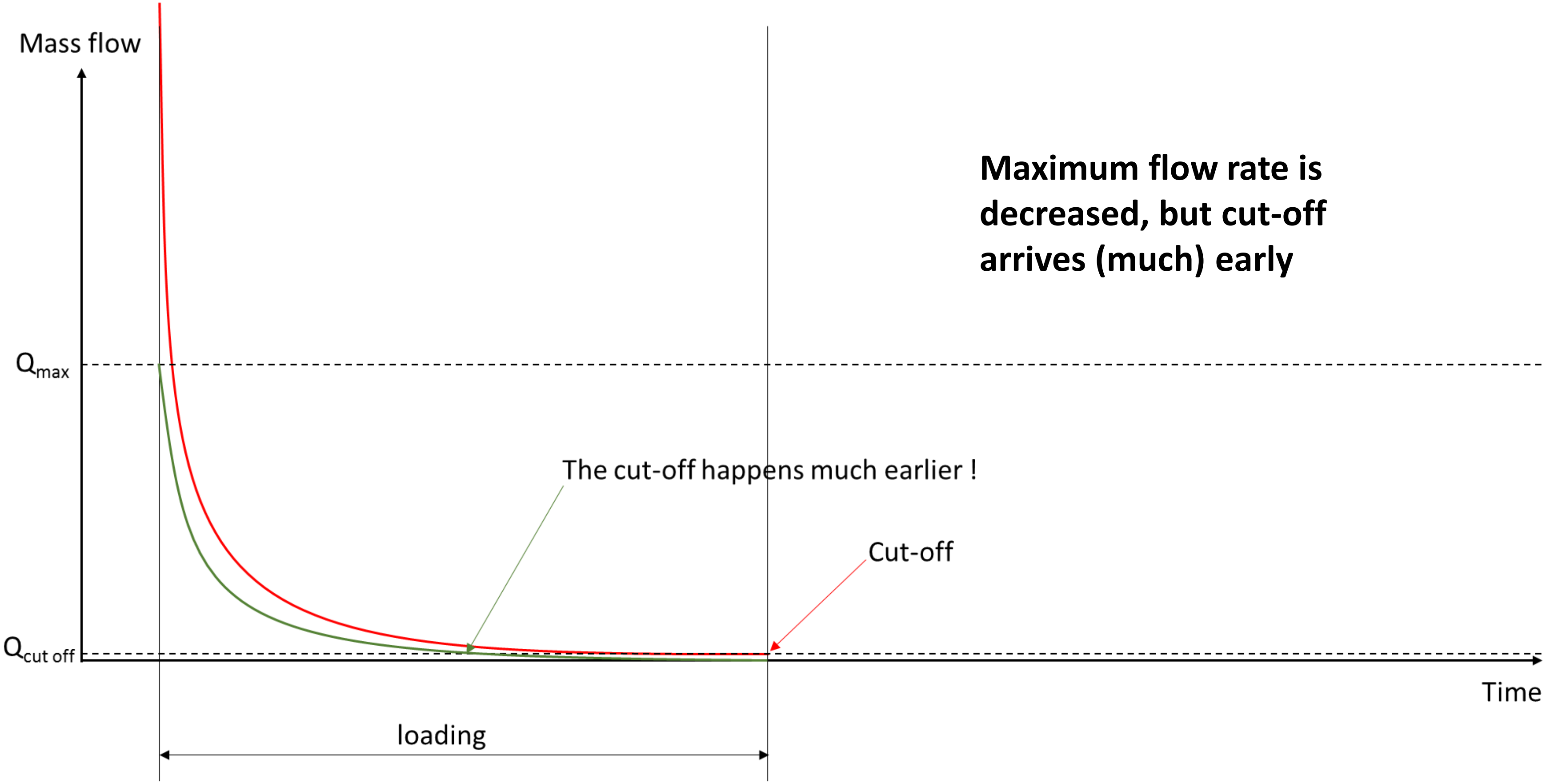
Recommendations

Problem using a needle valve without a pressure regulator



Maximum flow rate is decreased, but cut-off arrives (much) early

Mass flow through a NV : $\dot{m} = \sqrt{\frac{2}{\Lambda}\frac{M_{H_2}}{RT}S^2P\Delta P}$ ➔ need to maintain P and ΔP constant

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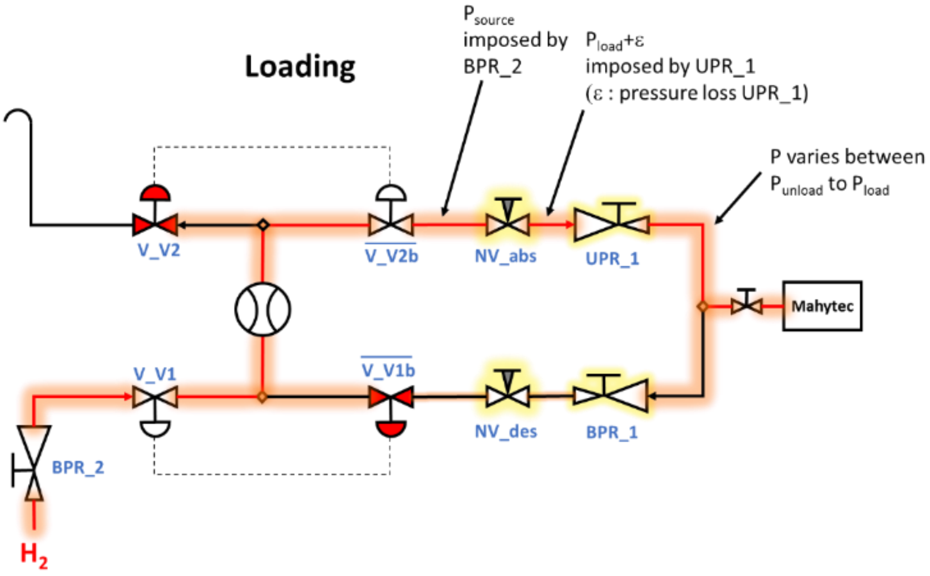
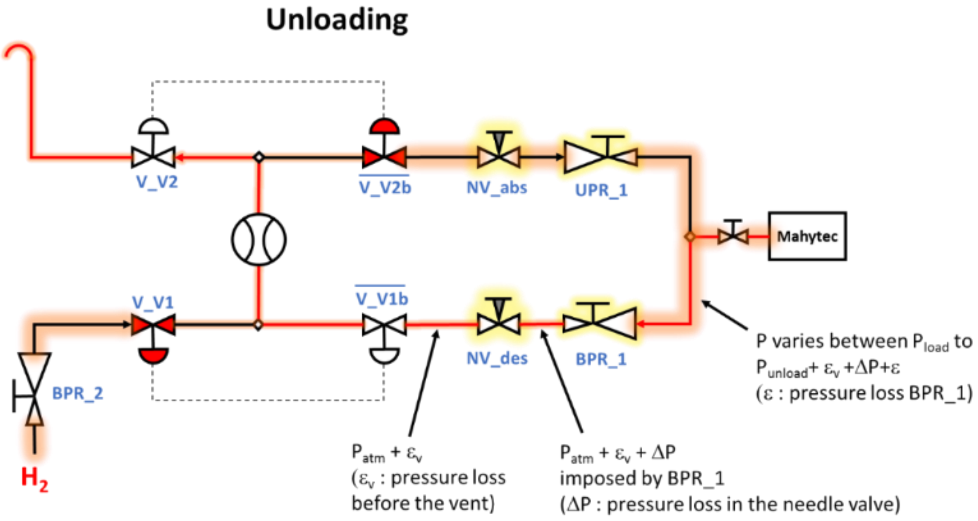
Recommendations

Proposed test bench when using needle valves

BPR	Backward pressure regulator
UPR	Upward Pressure Regulator
V_Vx	Valve
NV	Needle Valve





Mass flow works at P_{source}
Needle valve works at P_{source}

Mass flow works at ~P_{atm}
Needle valve works at ~P_{atm}

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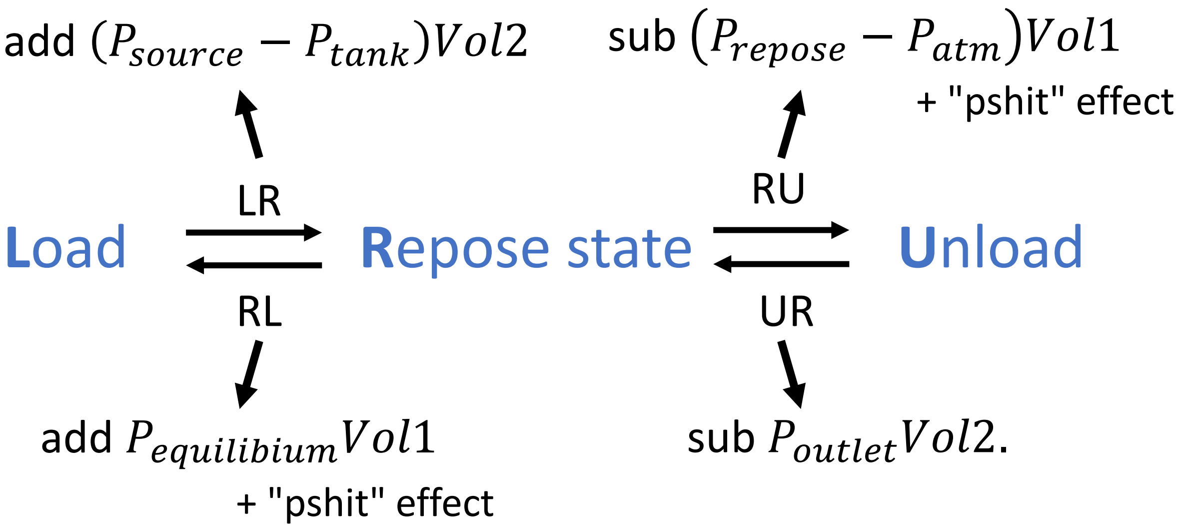
Recommendations

Detailled analysis of each operation



add $(P_{source} - P_{tank})Vol2$

sub $\left(P_{repose} - P_{atm}\right)Vol1$
+ "pshit" effect

LR

RU

Load

Repose state

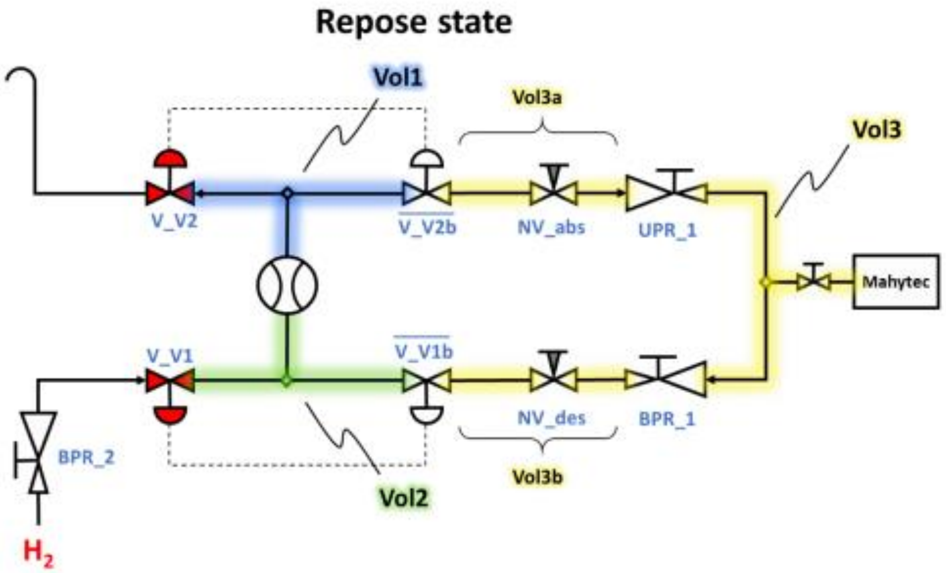
Unload

RL

UR

add $P_{equilibium}Vol1$
+ "pshit" effect

sub $P_{outlet}Vol2.$



To minimize "pshit" effect,
need to minimize
Vol1, Vol2, Vol3a, Vol4a

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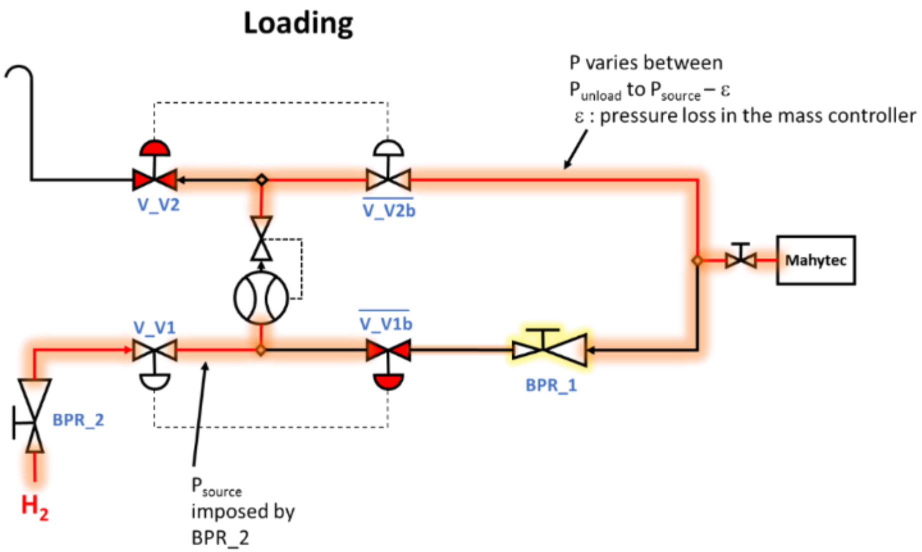
Recommendations

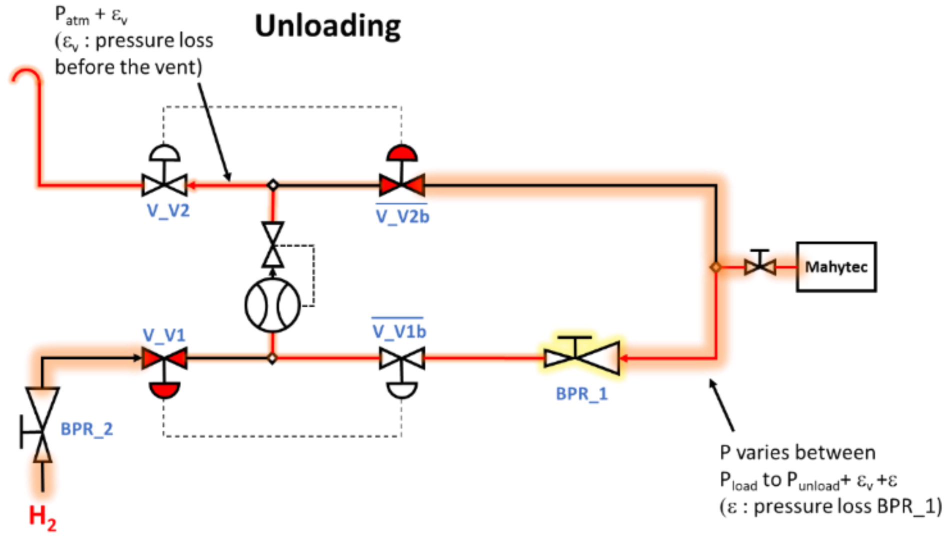
Proposed test bench when using mass flow controler

BPR	**Backward pressure regulator**
UPR	**Upward Pressure Regulator**
V_Vx	**Valve**
NV	**Needle Valve**



P varies between P_{unload} to $P_{source} - \varepsilon$
ε : pressure loss in the mass controller

P_{source} imposed by BPR_2



$P_{atm} + \varepsilon_v$
(ε_v : pressure loss before the vent)

P varies between P_{load} to $P_{unload} + \varepsilon_v + \varepsilon$
(ε : pressure loss BPR_1)

Mass flow works at P_{source}

Mass flow works at ~P_{atm}

+ same kind of correction that with needle valves (but no "pshit" effect)

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Conclusion & Perspectives

- Measuring capacity with thermal mass flowmeters seems to be the best solution

  But it is still delicate since a large range of flow rate and pressure are involved

- Thermal mass flowmeter, even though frequently used for measuring tank capacity, are not so accurate:

  A precision <2% sould be attained taking a few precautions

- Some incertainty origines have been detected / enlighten :
  - ✓ Some are understood and can be corrected by improving the test bench design

    Test bench geometries have been proposed, but it is necessary to test them

  - ✓ Some are not understood and necessitate more investigations

    Mass flow deviation at low pressures (Brooks)

      Understand why / Test others (Bronkhorst)

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