HYDROGEN REFUELLING STATION CALIBRATION WITH A TRACEABLE GRAVIMETRIC STANDARD

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

HYDROGEN REFUELLING STATION CALIBRATION
Related European Programs

- **This work has been realized within two European projects**

MetroHyVe – EURAMET EMPIR call

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

METROLOGY for HYDROGEN VEHICLES

20 project partners:

FCH-JU : FCH / OP / 196 : "Development of a Metering Protocol for Hydrogen Refuelling Stations"

Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

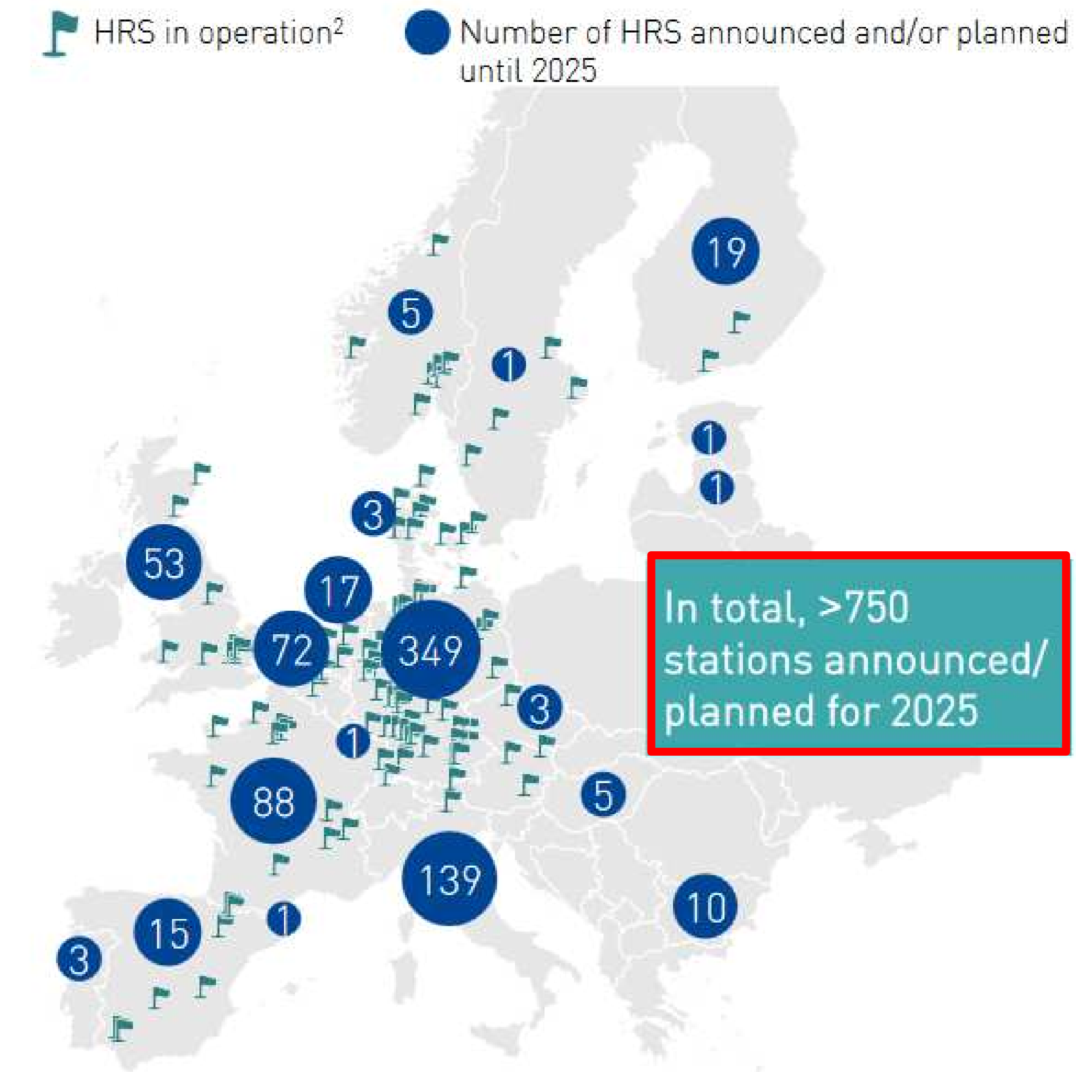
HYDROGEN REFUELLING STATION CALIBRATION
Road map of the presentation

- Background regarding HRS in Europe
- Basic operating principle of a HRS station
- Test protocol for HRS calibration (on-site) and primary gravimetric standard.
- Results from on-site measurements with the primary traceable gravimetric standard.
- Conclusions and perspectives

HYDROGEN REFUELLING STATION CALIBRATION
Background regarding HRS in Europe

- H2 HRS growth in Europe

Current and planned HRS in Europe



FCEV share in respective segment

	2030	2050
Small cars	2%	22%
Larger cars	5%	39%
Taxis	14%	61%
Vans/LCVs	8%	49%
Buses	6%	45%
Trucks	1%	35%

	2030	2050
Small cars	0%	14%
Larger cars	2%	28%
Taxis	8%	57%
Vans/LCVs	3%	30%
Buses	2%	25%
Trucks	<1%	21%

HYDROGEN REFUELLING STATION CALIBRATION
Background regarding HRS in Europe

- Why H2 dispensers are not certified yet?

  - Flow meters are not approved according to OIML R139 due to the absence of testing facilities (H2, 700 bar, ...)

  - OIML R139-2014 was not adapted for hydrogen dispensers

The standard has been revised in 2017-2018.
*New version issued on **Oct 2018**.*

→ Therefore, short-term solution for the approval H2 dispensers is necessary for the ramp-up of the HRS network in Europe

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HYDROGEN REFUELLING STATION CALIBRATION
Basic operating principle of a HRS station

- Basic principle and listing of the component:

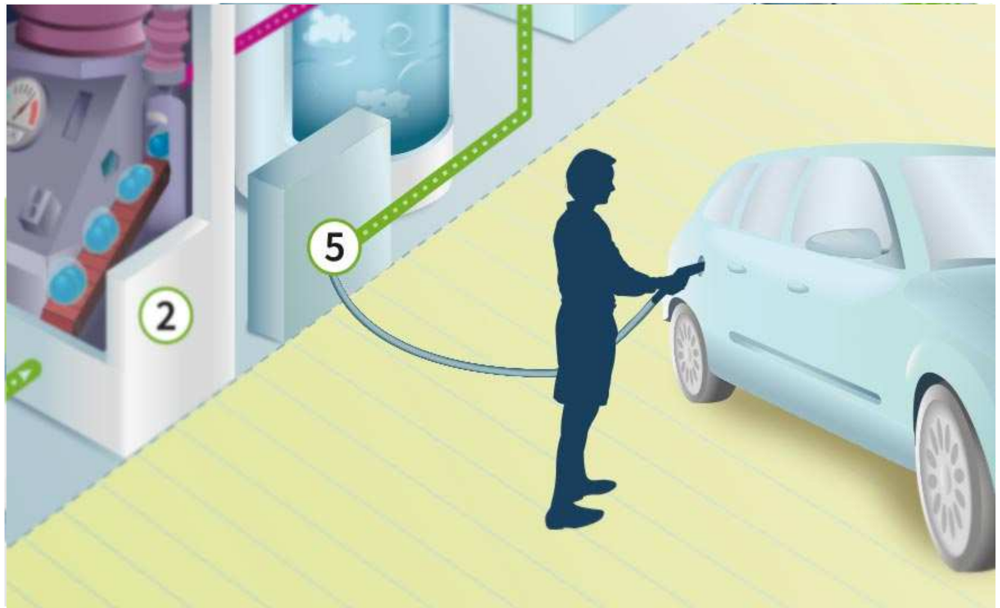
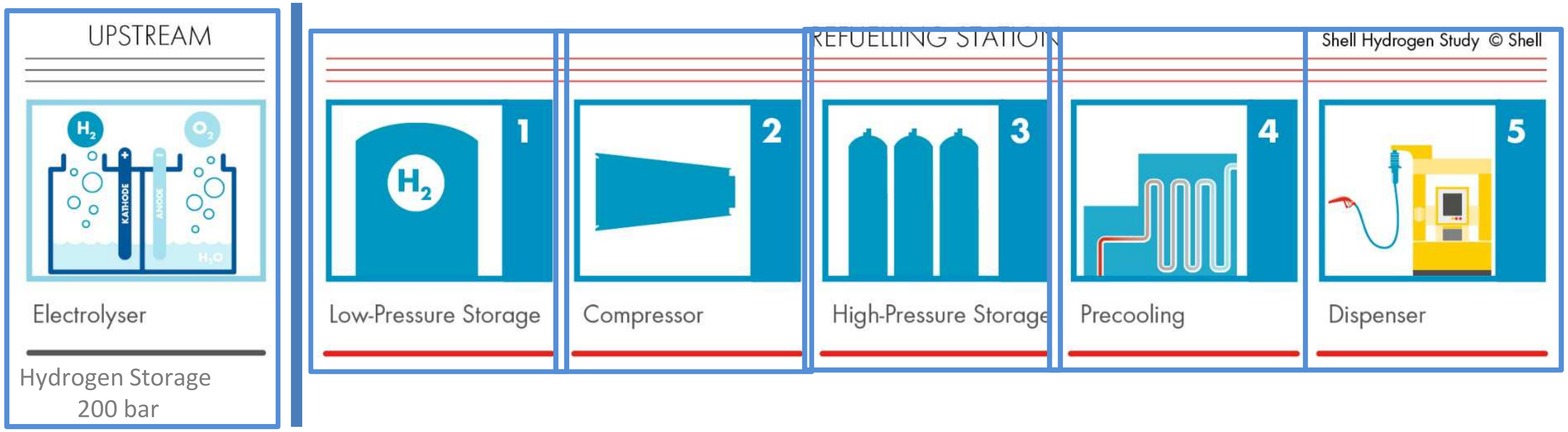


Photo courtesy of the California Fuel Cell Partnership



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HYDROGEN REFUELLING STATION CALIBRATION

Test protocol for HRS calibration (on-site)

- **Revision of the OIML R139 standard for gaseous dispensers**

  - OIML R139 revision initiated in **March 2017** to include specificities of Hydrogen dispensers
  - Accuracy classes have been largely discussed and revised:
    - **Class 2** & **Class 4** have been created for hydrogen service

Table 1 - MPE values

Accuracy class		MPE for the meter [in % *of the measured quantity value*]	MPE for the complete measuring system [in % of the measured quantity value]	
			at type evaluation, initial or subsequent verification	in-service inspection under rated operating conditions
For general application	1.5	1	1.5	2
For hydrogen only	2	1.5	2	3
	4	2	4	5

- In principle: **Class 2** is accepted for future stations, whereas **Class 4** is tolerated for existing stations

How to test a complete measuring system?

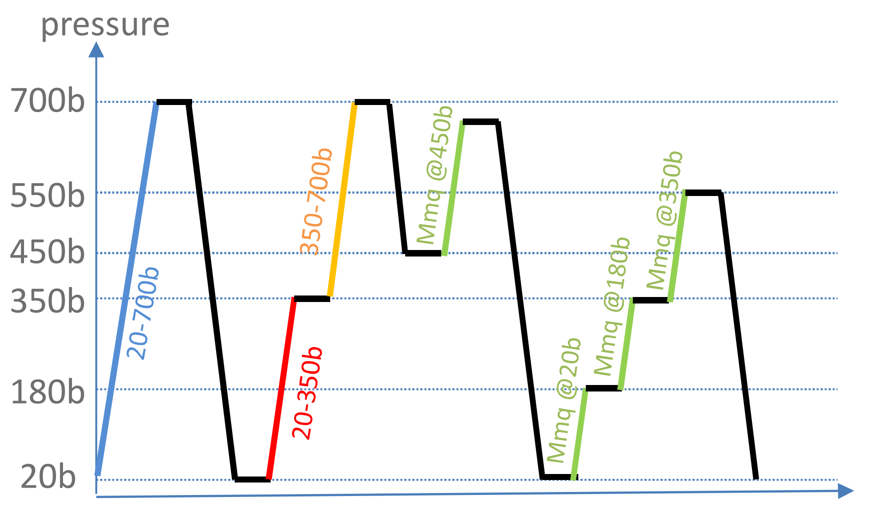
HYDROGEN REFUELLING STATION CALIBRATION
Test protocol for HRS calibration (on-site)

- **Accuracy tests based on *OIMLR139-2018***

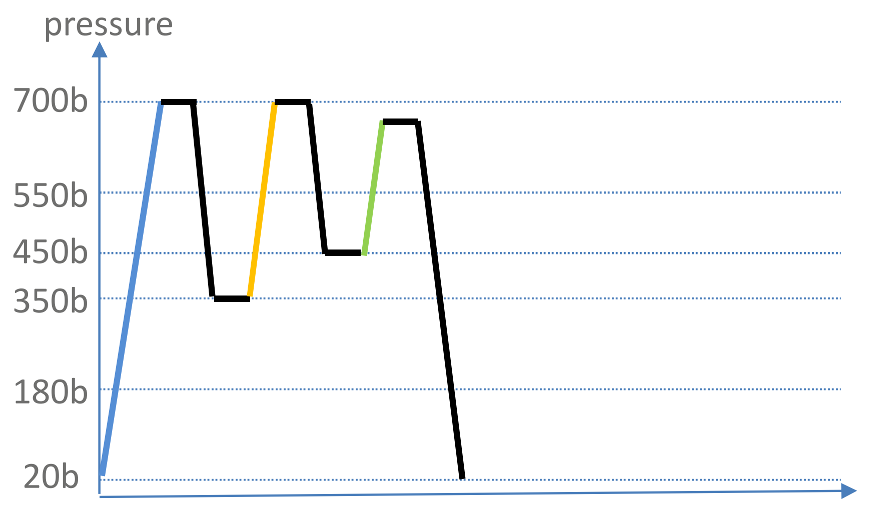
  – Full series of tests:

    – 1 full fillings 20-700 bar Automatic stop
    – 1 partial fillings 20-350 bar Manual stop
    – 1 partial fillings 350-700 bar Automatic stop
    – 4 MMQ fillings 1Kg
    with different starting pressure (450 bar - 20 bar - 180 bar - 350 bar) Manual stop

  – This series of tests is performed **4 times**



Tests done in this study



Tests required by OIML R139

Which kind of technologies have been tested ?

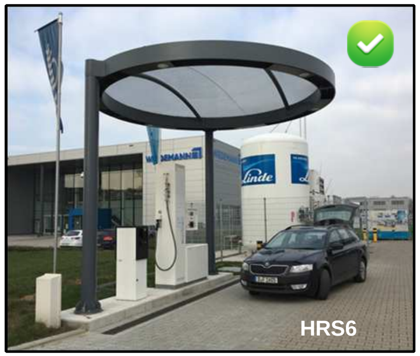
HYDROGEN REFUELLING STATION CALIBRATION

Test protocol for HRS calibration (on-site)

- **HRS technologies**

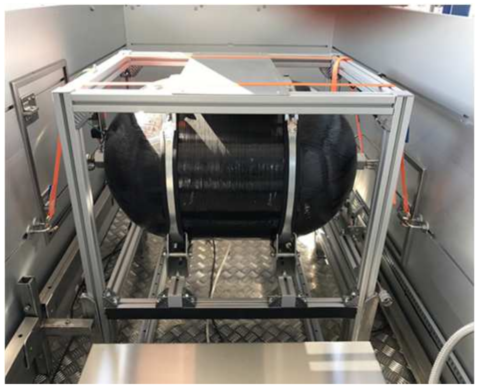
  – compressed gas or liquid hydrogen (cryo pump) & compressed gas (ionic compressor)
  – MFM located in the station, which can be far away from the dispenser / 3 different Coriolis manufacturers

- **HRS location (France, Germany (mainly) and Netherland)**



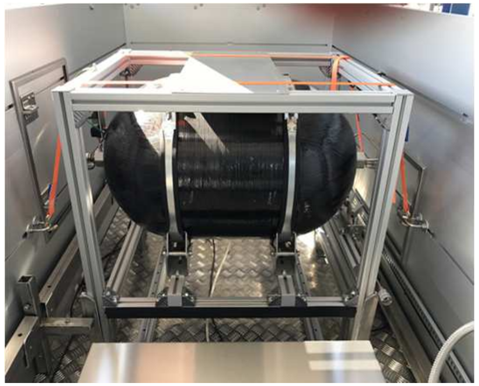
HYDROGEN REFUELLING STATION CALIBRATION
primary gravimetric standard (Air Liquide)

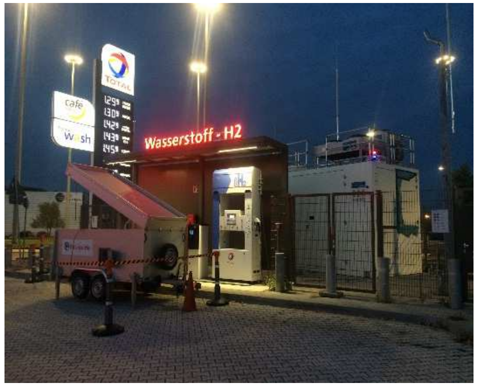
- **Main characteristics and design (Air Liquide + Cesame Exadebit)**
  - **High precision scale**: 150 kg resolution 0.2g, Ex-certified
  - **Composite tank type 4** of 104L (i.e. 4,0 Kg of Hydrogen at 700 bar, 15°C)
  - **Mobile** test bench (trailer) to be moved on each HRS
  - Trailer walls, doors and roof serve as **protection against wind**
  - Protection against fire (**TPRD**)
  - Possibility to remove the scale for transportation
  - Valve panel to **inert tank with N2** for transportation
  - Independent **vent stack** for depressurization of the tank



HYDROGEN REFUELLING STATION CALIBRATION
primary gravimetric standard (Air Liquide)

- **Testing device designed and manufactured by Air Liquide (with Cesame Exadebit)**
  - Certified by PTB (March 2018) as first reference standard for calibration, conformity assessment and verification of hydrogen refueling dispensers
    - Also accepted by LNE (France) and NMI Certin (Netherlands)
  - Fulfills metrological requirements as per OIML R139-2018
    - Uncertainty U < ⅕ MPE = 0,3%
    - Uncertainty budget defined in collaboration with PTB / LNE / Cesame Exadebit
- **CE approval**
  - Issue: tank is not designed as per PED, but **EC79** (on-board storage)
  - Long process with the Notified Body to get a Conformity Assessment according to PED
- **Testing equipment conform to Ex rules**





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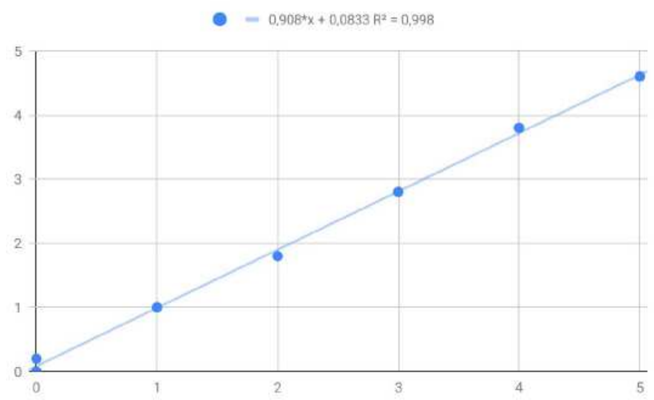
HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Typical planning of a testing week:**
  - Installation: 2-3h
  - Scale verification: 30 min
  - Accuracy test: 3 days
  - De-installation: 2-3h

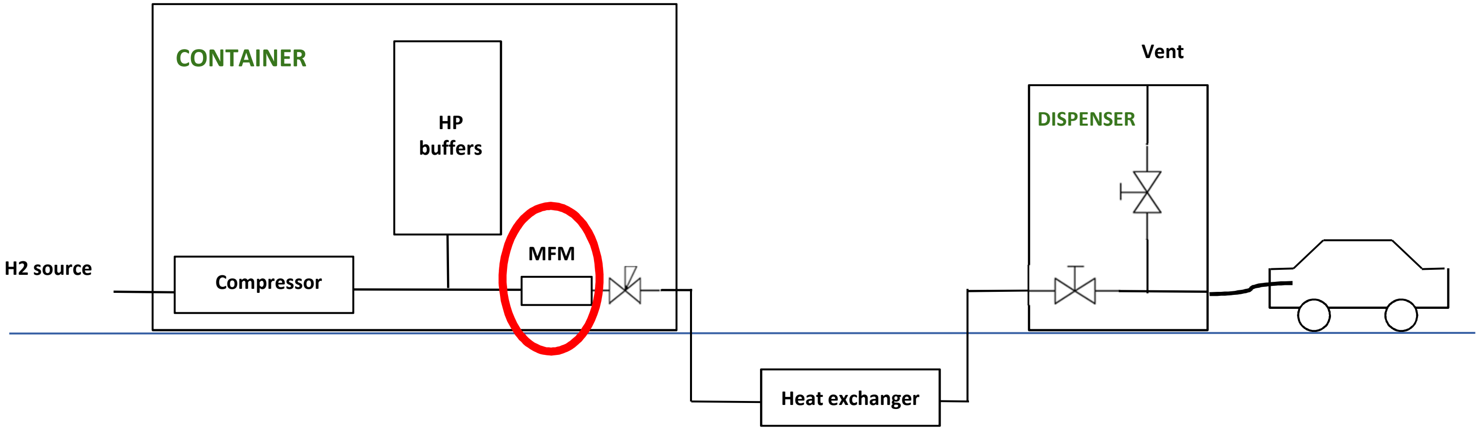
- **Scale verification**
  - Warm-up time required of about 1h30-2h
    - Scale must remain powered during nights to save time each morning
  - Verification using reference weights: 1 Kg / 2Kg / 4 Kg / 5 Kg:
    - One full verification on the 1st day
    - Then light verification each morning
  - Linear correction brought to mass measurements
    - Based on scale deviation measured each day



HYDROGEN REFUELLING STATION CALIBRATION

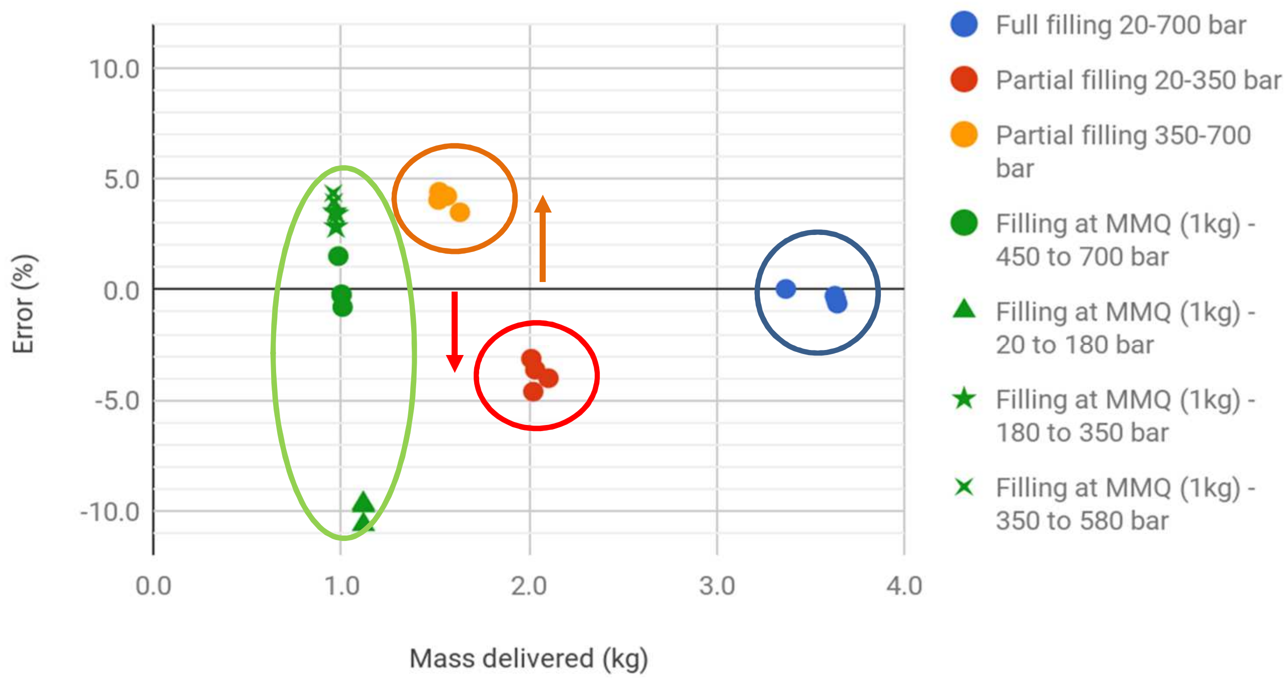
Results from on-site measurements with gravimetric standard

- Same configuration (called 1) of the measuring system:



HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Configuration 1: HRS2 (compressed gas) – CFM in the container**



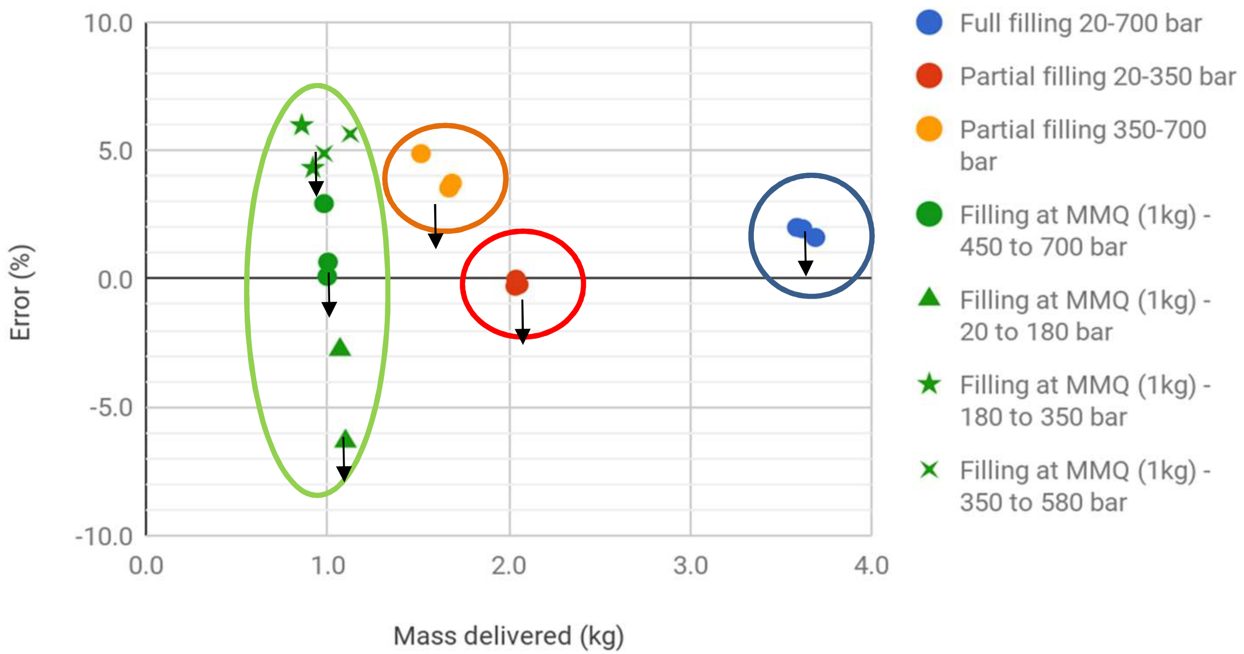
- Full filling : good repeatability – around 0
- Partial filling : negative offset (20-350bar)
- Partial filling : positive offset (350-700bar)
- Large scatter at MMQ depending on initial pressure

Is this tendency often seen with this configuration 1

HYDROGEN REFUELLING STATION CALIBRATION

Results from on-site measurements with gravimetric standard

- **Configuration 1: HRS1 (compressed gas) – CFM in the container**



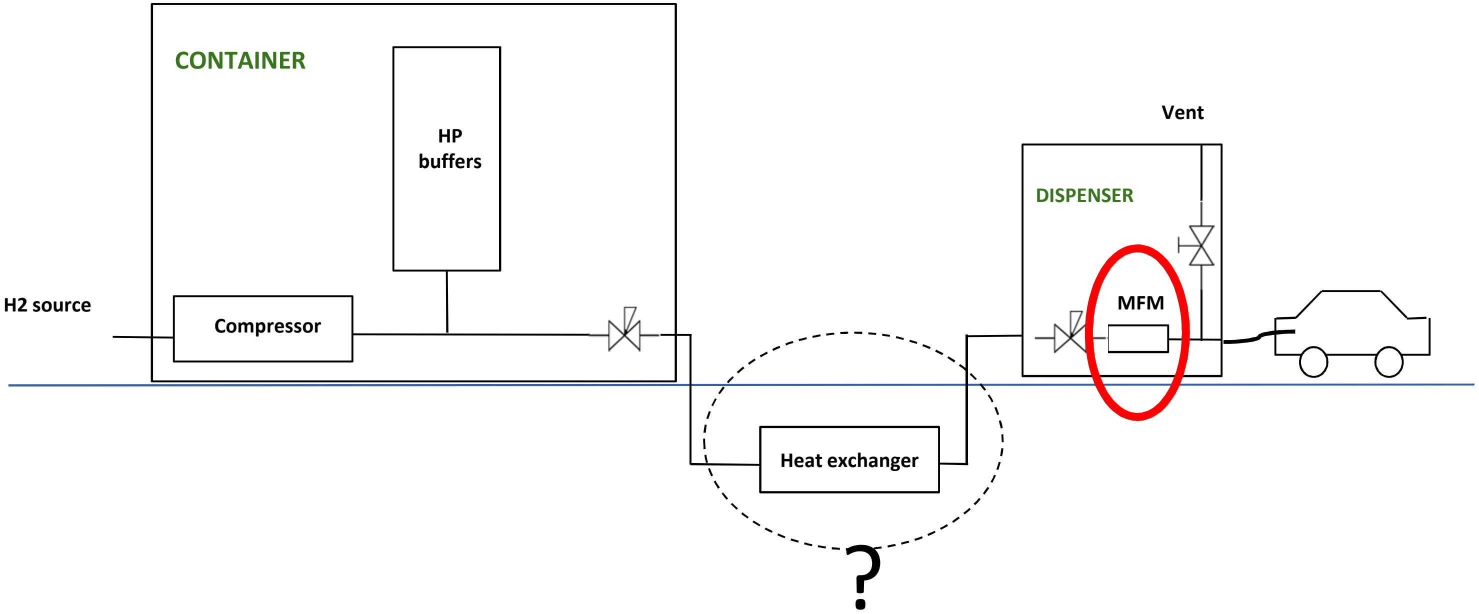
- The same trends are observed :
- For all fillings : good repeatability – ***but offset +2%***

This could be attributed to k factor in the MFM
Adjustment in Coriolis has not be realized during this test campaign
One adjustment is allowed by the OIML R139

What about other HRS configuration ?

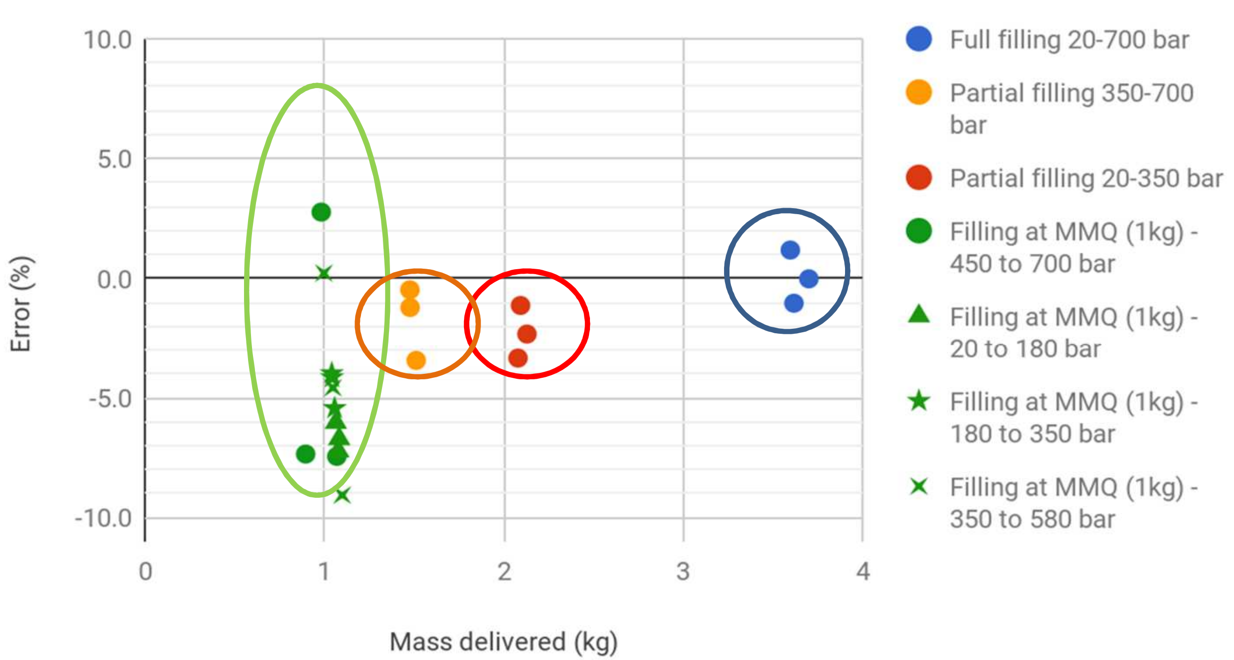
HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- Same configuration (called 2) of the measuring system:



HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Configuration 2: HRS7 (compressed gas) – CFM in the dispenser**

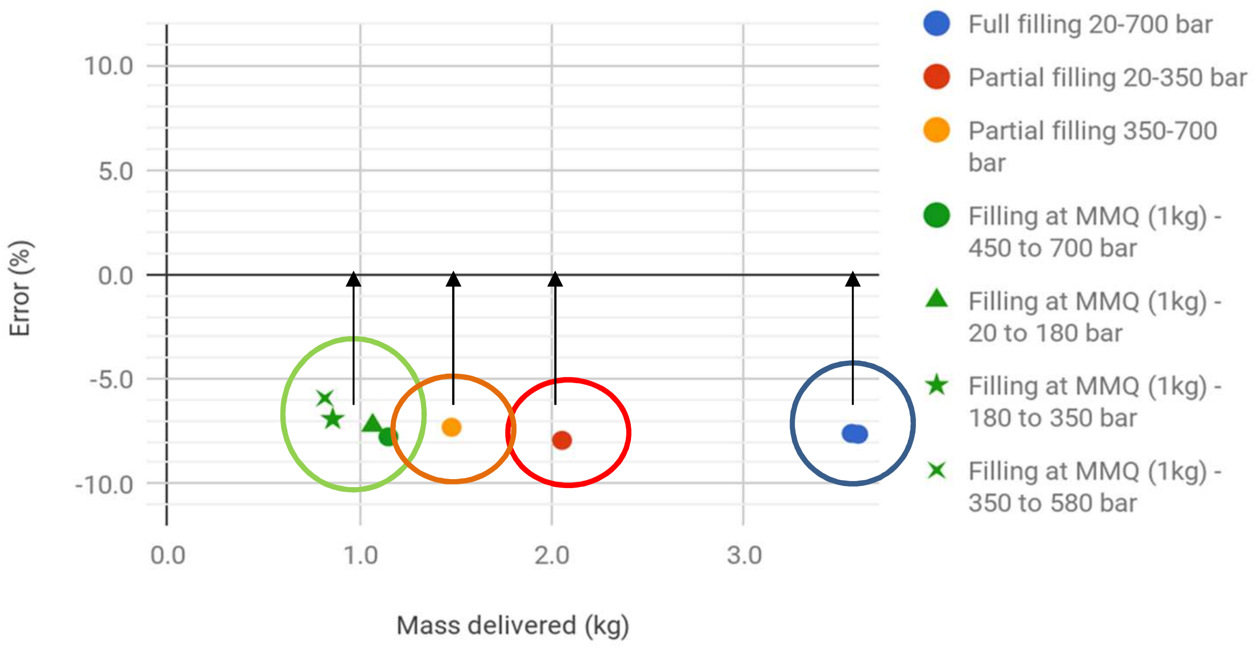


- Different results than previous HRS
- More dispersion on the test results (other brand of MFM)
- ***Constant deviation seems observed → Icing issue***

***Remark** : weather was bad – high humidity / cold*
Venting was taken into account – no indication how

HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Configuration 2: HRS6 (Liquid H2) – CFM in the dispenser**



- Large negative offset
- Results are centre around -7%
- ***If a correction is applied to the CFM, this configuration could reach a class 1.5 in the OIML R139 classification***
- ***Only one set before HRS failure.***

Summary of all experiments and accuracy class for HRS

HYDROGEN REFUELLING STATION CALIBRATION

Results from on-site measurements with gravimetric standard

MEAN VALUES	CONFIGURATION 1					CONFIGURATION 2	
	HRS1 *(based on adjusted values)*	**HRS2**	**HRS3**	**HRS4** *(based on adjusted values)*	**HRS5**	**HRS6** *(based on adjusted values)*	**HRS7**
Full fillings 20-700 bar	0,00%	-0,32%	0,52%	0,00%	0,50%	*0,00%*	0,04%
Partial fillings 20-350 bar ***(*)***	-2,03%	-3,84%	-2,46%	-0,83%	-3,89%	*-0,31%* (*)	-2,26%
Partial fillings 350-700 bar	2,19%	4,05%	0,72%	1,00%	4,58%	*0,31%* (*)	-1,71%
Filling at MMQ 450 to 700 bar	-0,63%	0,08%	1,99%	0,50%	4,84%	*-0,14%* (*)	-4,01%
Filling at MMQ 20 to 180 bar ***(*)***	-6,41%	-10,02%	-9,95%	-1,71%	-6,75%(*)	*0,40%* (*)	-6,65%
Filling at MMQ 180 to 350 bar ***(*)***	3,29%	3,28%	-5,13%	0,94%	0,51%(*)	*0,71%* (*)	-4,51%
Filling at MMQ 350 to 580 bar ***(*)***	3,41%	3,69%	-1,08%	0,71%	4,63%(*)	*1,70%* (*)	-4,47%
CLASS OIML R139	**4**	**4**	**2**	**2**	**4**	**2**	**4**

Legend:

Green = all values are within the limits (MPE)

Orange = mean value is within the limits (or very close to the limits), but some single values are out of the limits (MPE)

Red = all values are out of the limits (MPE)

(*) single value

(*) tests out of OIML R139:2018 scope

Explanations for the results

HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

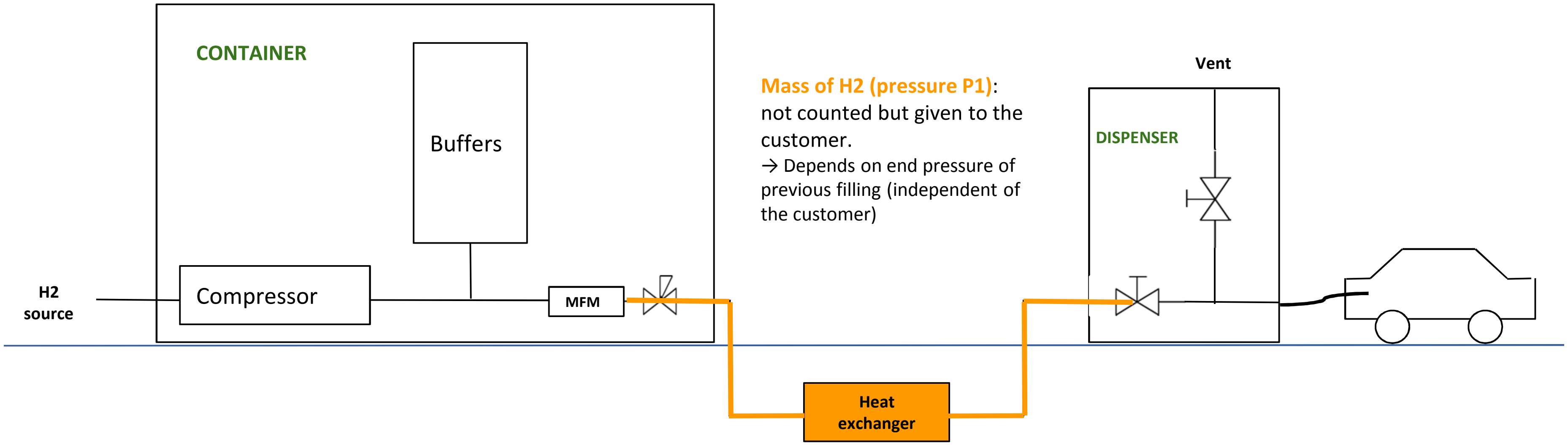
- **Good reliability of the testing device in ambient conditions** (hot temperatures, moderate wind, cold and humid conditions in winter)
  - Icing phenomenon to be **considered** and better quantified in the uncertainty budget
- **Influence of the type of MFM:**
  - Three models tested in different configurations
  - Good precision obtained with M1 & M2 MFM (cf. Full fillings) and good overall repeatability
  - Remark on the M3:
    - Dispersion seems more important
    - Further tests required to clearly conclude on the performance of this MFM
- **Influence of the measuring system configuration (distance between the MFM and the nozzle):**
  - **Configuration 2** show lower errors than configuration 1

Why?

HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

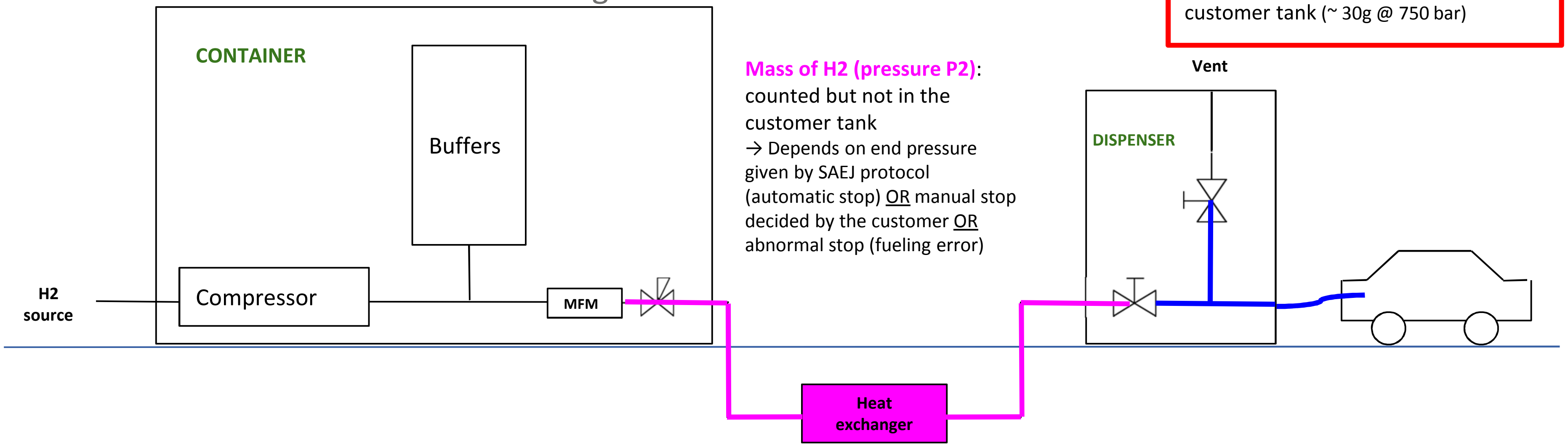
- **Influence of distance between MFM and dispenser: Configuration 1**

  – Situation at beginning of a fueling



  – Situation at the end of a fueling

Vented quantity: counted, but not in customer tank (~ 30g @ 750 bar)



HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Influence of distance between MFM and dispenser: Configuration 1**

  - If **P1** ~ **P2**: the customer pays ***exactly*** the quantity delivered in his tank
    - Initial mass of H2 is replaced by the *same* quantity at end of fueling

m_delivered ~ m_invoiced

  - If **P1** > **P2**: the customer get ***more*** hydrogen than the quantity invoiced
    - Initial mass of H2 is replaced by a *lower* quantity at end of fueling

m_delivered > m_invoiced ***(negative error)***

  - If **P1** < **P2**: the customer get ***less*** hydrogen than the quantity invoiced
    - Initial mass of H2 is replaced by a *higher* quantity at end of fueling

m_delivered < m_invoiced ***(positive error)***

APPLICATION:

● Full fillings 20-700 bar

● MMG (1kg) 450-700 bar

● Partial fillings 20-350 bar

▲ MMG (1kg) 20-180 bar

● Partial fillings 350-700 bar

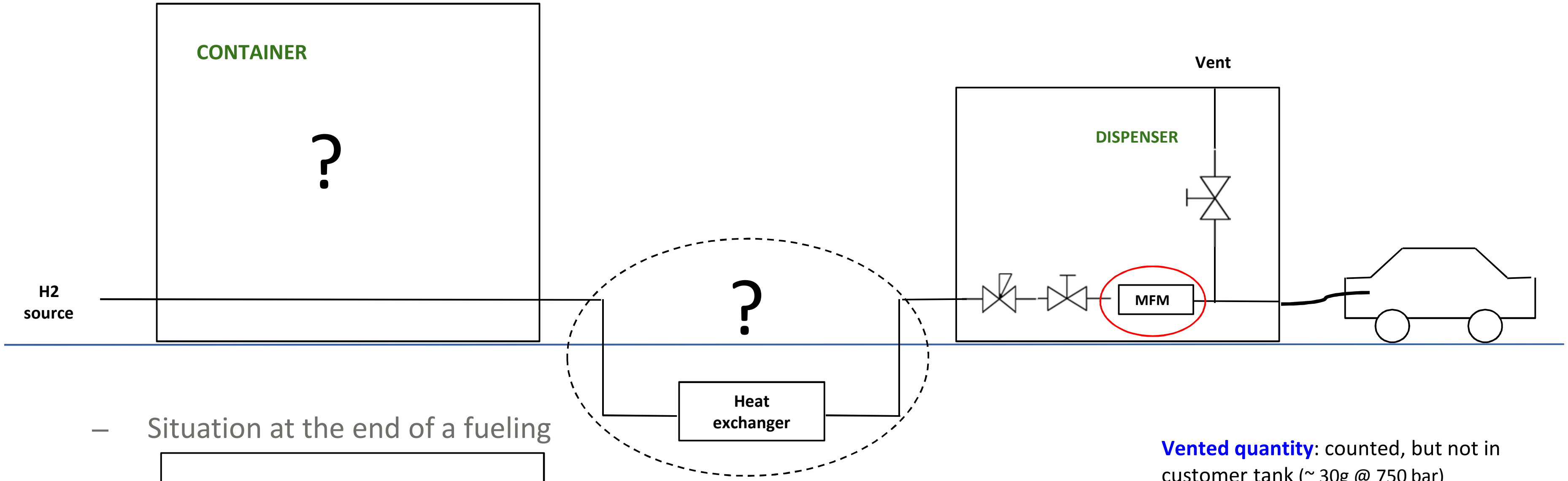
★ MMG (1kg) 180-350 bar

MMG (1kg) 350-580 bar

- **Strong influence of the distance between the MFM and the dispenser**
  - **The longer is the distance (or volume), bigger is the error**
  - **Larger pressure difference in the pipe at beginning and end of fueling leads to a bigger error**
    - **Example: MMQ fueling at 450 bar and 20 bar initial pressure**
  - **If the volume of piping is known then errors can be calculated and corrected**

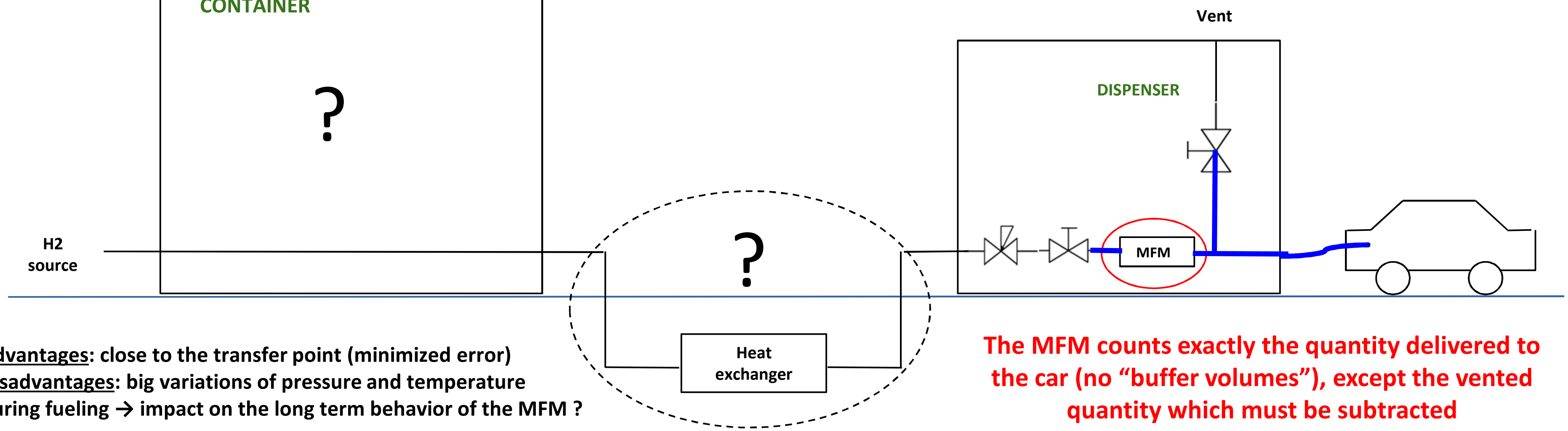
HYDROGEN REFUELLING STATION CALIBRATION
Results from on-site measurements with gravimetric standard

- **Influence of distance between MFM and dispenser: Configuration 2**
  - Situation at beginning of a fueling



  - Situation at the end of a fueling

Vented quantity: counted, but not in customer tank (~ 30g @ 750 bar)



Advantages: close to the transfer point (minimized error)
Disadvantages: big variations of pressure and temperature during fueling → impact on the long term behavior of the MFM ?

The MFM counts exactly the quantity delivered to the car (no "buffer volumes"), except the vented quantity which must be subtracted

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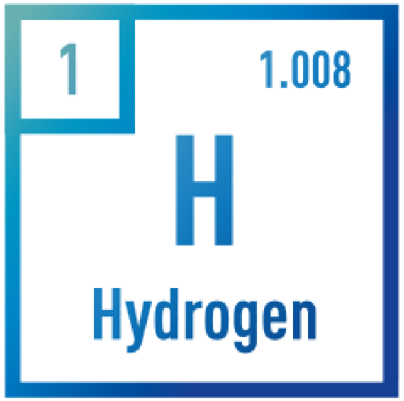
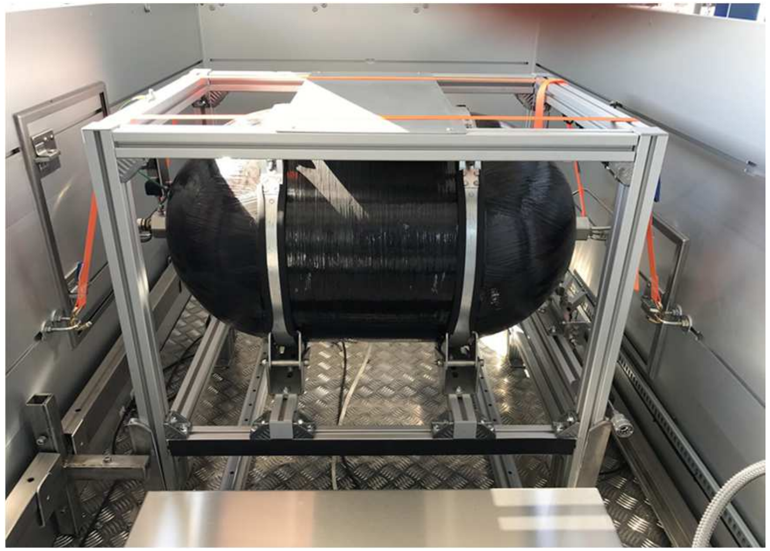
HYDROGEN REFUELLING STATION CALIBRATION
Conclusions and perspectives

- **A primary test bench as been designed and developed for hydrogen refueling station calibration.**
- **An intensive test campaign has been realized in Europe (7 HRS).**
- **The accuracy classes has been found to mainly comply with Class 4 (for existing stations).**
- **The main errors have been measured and some hypothesis have been proposed to understand the difference between two main configurations – Configuration 2 seems more accurate but caution has to be taken regarding operating conditions.**
- **Need to make comparison between primary standard for hydrogen stations and develop new metrological framework for periodic verification to speed up the test campaing**
- **Need to consider other kind of technologies (bicycles, buses and train) and adapt our reference for these ranges of application.**

HYDROGEN REFUELLING STATION CALIBRATION
Conclusions and perspectives

- Thank you !





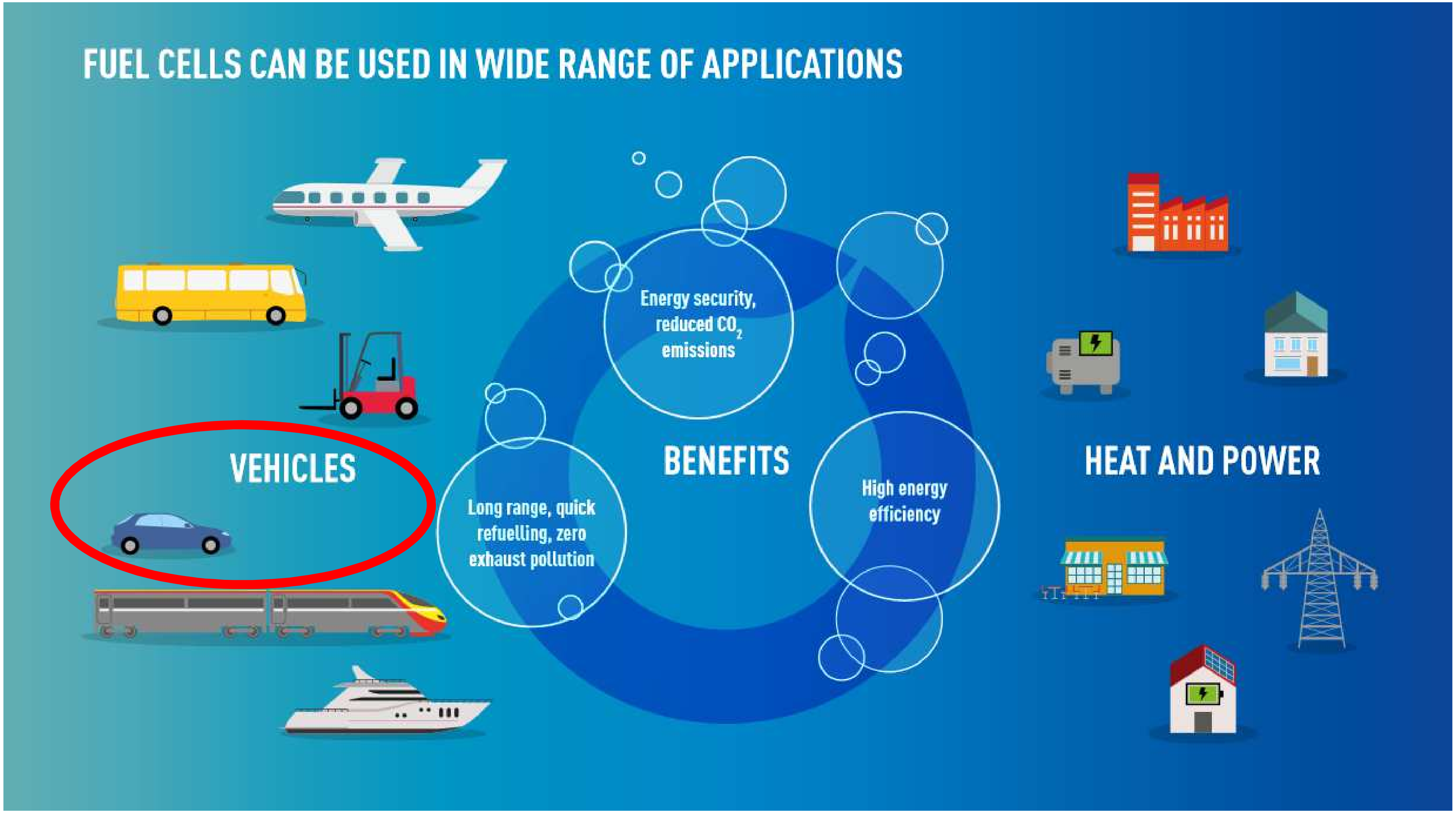
HYDROGEN REFUELLING STATION CALIBRATION

Backup slides

HYDROGEN REFUELLING STATION CALIBRATION

Background regarding HRS in Europe

- Hydrogen & Fuel cells have several roles in decarbonizing major sectors of the economy



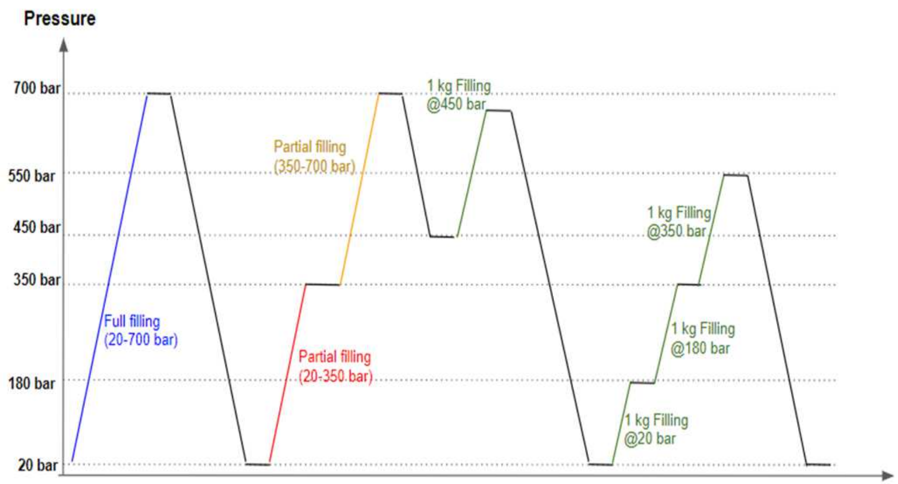
HYDROGEN REFUELLING STATION CALIBRATION
Test protocol for HRS calibration (on-site)

- **Accuracy tests based on *OIMLR139-2018***

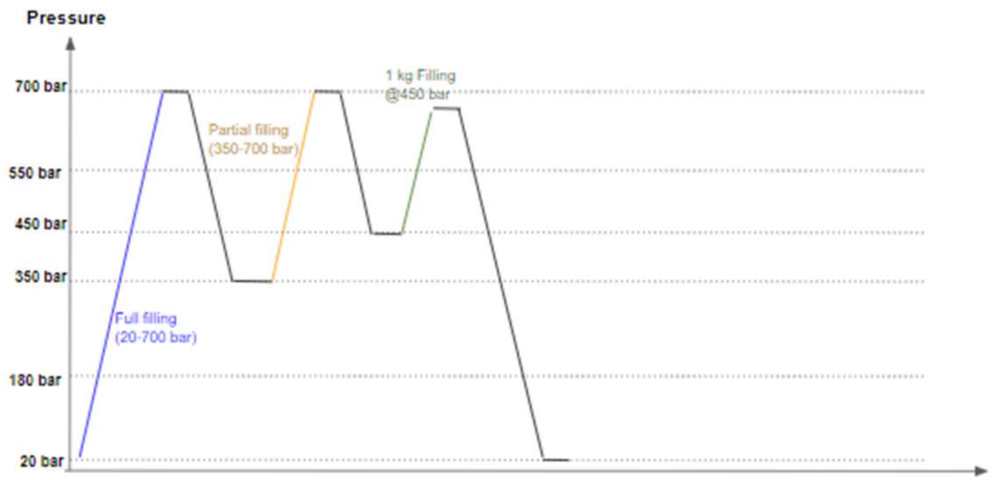
  – Full series of tests:

– 1 full fillings	20-700 bar	Automatic stop
– 1 partial fillings	20-350 bar	Manual stop
– 1 partial fillings	350-700 bar	Automatic stop
– 4 MMQ fillings	1Kg	
with different starting pressure	(450 bar - 20 bar - 180 bar - 350 bar)	Manual stop

  – This series of tests is performed **4 times**



Tests done in this study



Tests required by OIML R139

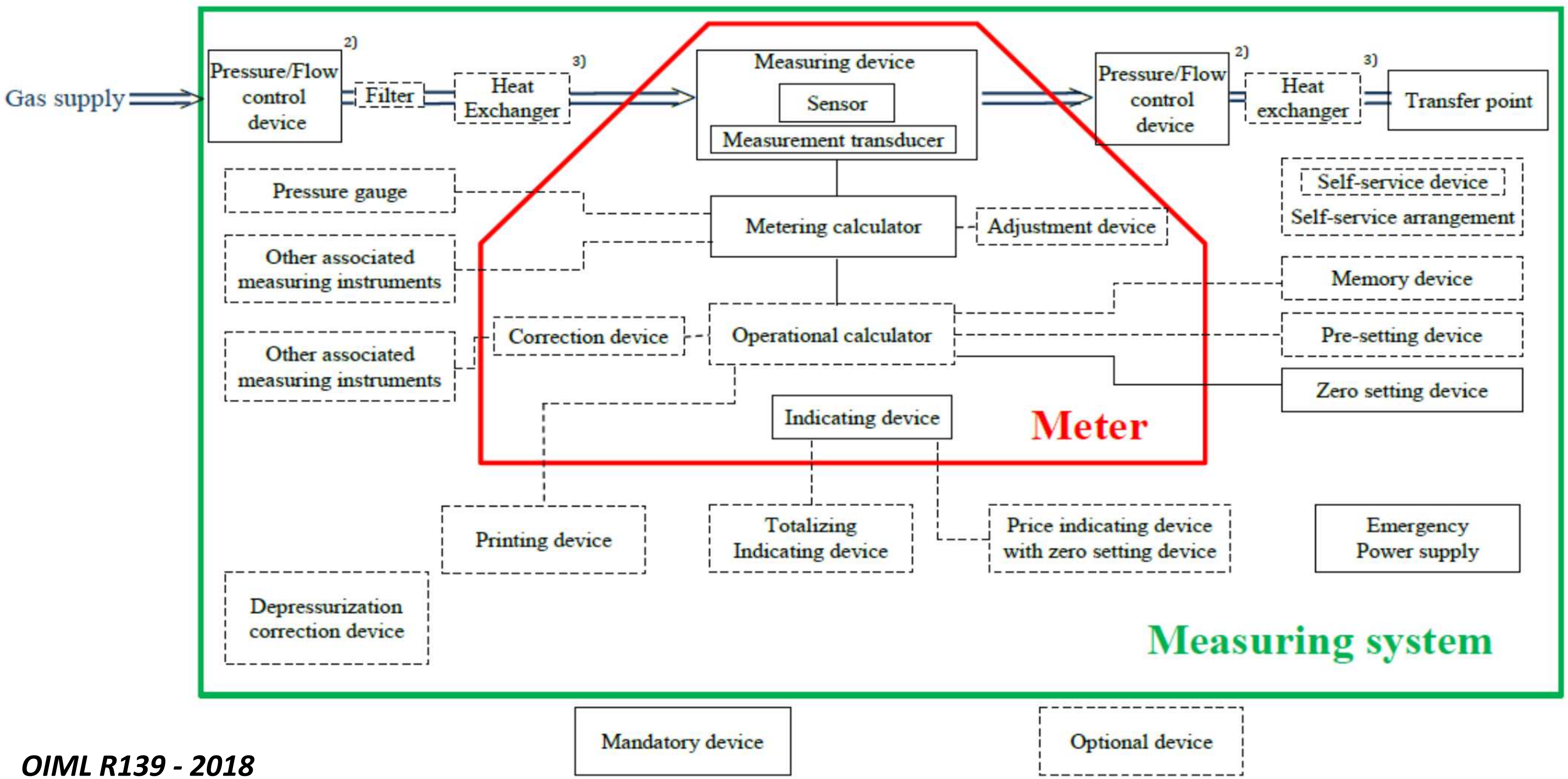
Which kind of technologies have been tested ?

HYDROGEN REFUELLING STATION CALIBRATION

Basic operating principle of a HRS station

- Basic principle and listing of the component: The OIML R139 [2] describes a HRS as a measuring system which should include at least:

a) meter; b) pressure and/or flow control device; c) emergency power supply; d) transfer point;
e) gas piping; f) zero-setting device.



OIML R139 - 2018

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primary gravimetric standard (Air Liquide)

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  - Fulfills metrological requirements as per OIML R139-2018
    - Uncertainty U < ⅕ MPE = 0,3%
    - Uncertainty budget defined in collaboration with PTB / LNE / Cesame Exadebit

- **Uncertainty sources**

Ref.	Cause of unertainty	Uncertainty U(xi)		Probability density function		Type of uncertainty	Coefficient of sensitivity		Contribution to the global uncertainty	
		Value	Unit	Type	Divisor	u(xi)	ci	Unit	[ci * u(xi)]^2	in %
B.0	Repeatability of measurements	0,70	g	Rectangular	1,73	4,04E-01	1	g	1,63E-01	13,45%
B.1	Eccentric loads	0,20	g	triangular	2,45	8,16E-02	1	-	6,67E-03	0,55%
B.2.a	Scale resolution when empty	0,20	g	triangular	2,45	8,16E-02	1	-	6,67E-03	0,55%
B.2.b	Scale resolution when loaded	0,20	g	triangular	2,45	8,16E-02	1	-	6,67E-03	0,55%
B.3	Uncertainty of reference weights	0,07	g	Normal	2,00	3,50E-02	1	-	1,23E-03	0,10%
B.4	Scale reliability (temperature effects)	0,20	g	Normal	2,00	1,00E-01	1	-	1,00E-02	0,82%
B.5	Non linearity of the scale	0,50	g	Rectangular	1,73	2,89E-01	1	-	8,33E-02	6,86%
B.6	Air density (ambiant conditions)	0,16	g	Rectangular	1,73	9,24E-02	1	-	8,53E-03	0,70%
B.7	Effect of temperature on the scale	0,20	g	Rectangular	1,73	1,15E-01	1	-	1,33E-02	1,10%
B.8	Connection / disconnection influence	0,60	g	Rectangular	1,73	3,46E-01	1	-	1,20E-01	9,89%
B.9	Buyoncy (stability of iar density at beginning and end of filling, including vessel expansion)	0,95	g	Rectangular	1,73	5,48E-01	1	-	3,01E-01	24,78%
B.10	Short time drift of balance (temperature effect, wind, balance performance, etc...)	0,40	g	Rectangular	1,73	2,31E-01	2	-	2,13E-01	17,57%
B.11	Water condensation	0,40	g	Rectangular	1,73	2,31E-01	2	-	2,13E-01	17,57%
B.12	Zero stability after depressurization	0,40	g	Rectangular	1,73	2,31E-01	1	-	5,33E-02	4,39%
B.13	Influence of the grouding	0,20	g	Rectangular	1,73	1,15E-01	1	-	1,33E-02	1,10%
	Combined uncertainty	$u_c = \sqrt{\sum_i c_i^2 u_i^2}$		1,35	g			TOTAL =	1,21E+00	
	Expanded uncertainty (k = 2)	$U_E \ (K = 2)$		2,70	g		**Class 1,5**	**Class 2**		
	Relative expanded uncertainty	$U_r = \frac{U(X)}{X} \times 100$		**0,270**	%	**Criteria**: 1/5 of MPE	**0,3**	**0,4**		