METROLOGY for HYDROGEN VEHICLES

INFRASTRUCTURE FOR H_2 CALIBRATION

development of a primary test bench for performing traceable calibration of hydrogen flow meters at pressures up to 875 bar with target accuracy 1.5 % and following technical requirements stipulated in OIML R 139-1 and international standard SAE J2601

EMPIR EURAMET

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www.MetroHyVe.eu

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Contents

Introduction

Nowadays, the hydrogen market is growing fast and hydrogen is considered for many applications like mobility. Some countries in Europe are investing a lot of money to develop this vector. As an example, Germany just signed for a large hydrogen plan for 6 billion euros. It is realistic to believe that more and more hydrogen refueling stations will be built in the next 10 years.

Up to now, there is no testing facility in the world that can provide a traceability route to the flow meter manufacturers (at the operating conditions – 700 bar / -40 °C). It is a real problem since the legal metrology must be applied when people are trading energy between providers to customers. The national metrological institute should have a dedicated testing facility to perform the calibration of these hydrogen mass flow meters at high pressure (like what they are doing for natural gas for example).

Within the MetroHyVe project, alternative fluids used on current infrastructures (low pressure with nitrogen for example) have been tested. Only a limited set of data is available and the results do not allow to conclude that the calibration approach using substitute substances to hydrogen can be used with total confidence to obtain a complete description of the characteristics of the CFM with hydrogen. More data on the equivalence of calibration results with different fluids are clearly needed.

The MetroHyVe partners have developed primary standards for hydrogen field-testing. It allows the certification of the complete measuring system (HRS) but not of the individual flow meter of the HRS.

If a HRS manufacturer wants to build a certified system, all the equipment needs to be certified. This is not possible now for OIML R139:2018 using only hydrogen as testing gas. A laboratory primary standard will be required and if the market continues to grow as the same level in the next decade, the existence of a dedicated test bench for high-pressure calibration will be justified or there must be total confidence in using substitute substances to hydrogen for characterizing flow meters

This report will provide information on a possible design of a primary test facility for performing high-pressure calibrations for hydrogen flow meters up to 70 MPa and temperature varying from 20°C to - 40°C. This report will also give some numbers for an investment budget and an uncertainty budget assessment.

Requirements for calibration and validation of a HRS: OIML R139:2018

When a hydrogen station manufacturer wishes to sell its product to its customer whose use is intended for the public, the station manufacturer must comply with the associated standards resale of energy to individuals (legal metrology) to ensure reliability in the transaction. There was no (specific) reference text on the sale of hydrogen (HRS) to individuals so far. The "Organisation Internationale de Métrologie Légale - OIML" had a recommandation on compressed gas (natural gas mainly) and has therefore been revised in this direction in order to integrate the technical constraints to the use of this high-pressure gas. Its most recent edition has been issued in October 2018. The three components of the international recommendation are available on the OIML website

(https://www.oiml.org/en/files/pdf_r/r139-pe18.pdf).

The text is divided into three parts, constituting three separate documents:

1. R139-1 - Metrological and Technical Requirements (52 pages)
2. R139-2 - Metrological controls and performance tests (63 pages)
3. R139-3 - Test Report Format (65 pages)

Metrological and technical requirements (document R139-1)

This first section describes the elements that constitute the measurement system and therefore items that need to be tested for certification of the measuring system.

Figure 1 below summarizes the mandatory and optional elements.

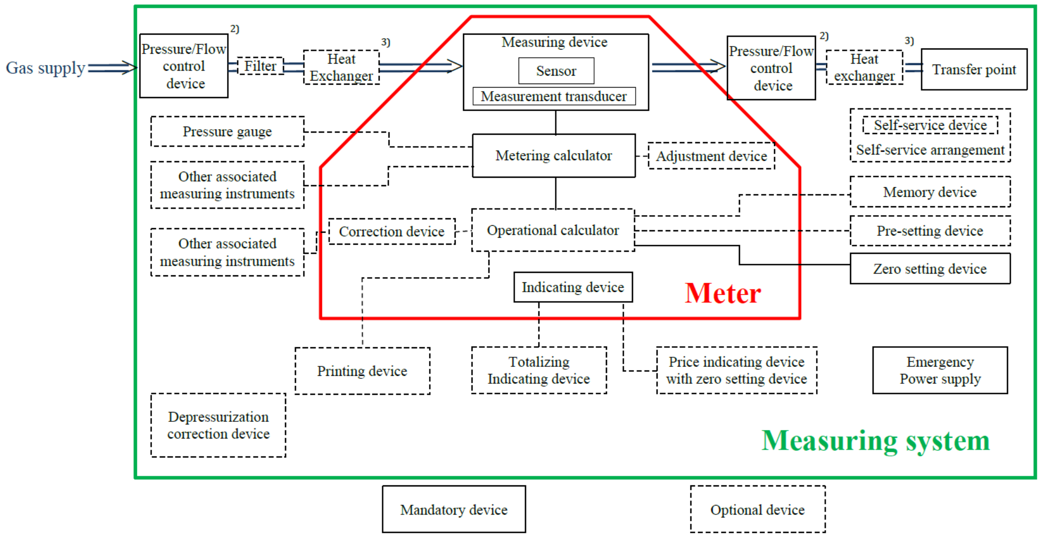

Figure 1: Constituents of a typical compressed gaseous fuel measuring system for vehicles.

Metrological obligations for the measurement system:

In this paragraph will be listed (in no order of importance) all mandatory metrological requirements to obtain OIML R139 certification: 2018 for a HRS at 700 bars. Other prescriptions will not be noted (for example, the case of the CNG).

1. The MPE are defined in the Table 1 below

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

Table 1: MPE values

There are 2 main categories in this table, the MPE for the meter itself (on the left side) and the MPE for the complete measuring system.

It is important to note that there are 2 classes for hydrogen. Class 4 will be mainly accepted for existing stations whereas class 2 shall be chosen for new HRS. As an example, the MPE during a type approval of a new HRS (class 2) is 2%.

2. In the case of the measurement of the 'smallest measurable amount', called MMQ in English (Minimum Measured Quantity) , the MPE is twice the value of the Table 1 above (1.5.2.3).

$$E_{min} = 2 \times MMQ \times R_{MPE} \text{ [g; kg]}$$

where: R_{MPE} = the maximum permissible error ratio according to 5.2.1 (in 5.2.1 expressed in percentages of the measured quantity value);

MMQ = the specified minimum measured quantity according to 5.3.2.

It gives the

Accuracy class	E_{min} [g; kg]		
	for the meter	for the complete measuring system	
		at type evaluation, initial or subsequent verification	at in-service inspection
1.5	0.02 MMQ	0.03 MMQ	0.04 MMQ
2	0.03 MMQ	0.04 MMQ	0.06 MMQ
4	0.04 MMQ	0.08 MMQ	0.1 MMQ

Table 2 below:

Accuracy class	E_{min} [g; kg]		
	for the meter	for the complete measuring system	
		at type evaluation, initial or subsequent verification	at in-service inspection
1.5	0.02 MMQ	0.03 MMQ	0.04 MMQ
2	0.03 MMQ	0.04 MMQ	0.06 MMQ
4	0.04 MMQ	0.08 MMQ	0.1 MMQ

Table 2: E_{min} values for all accuracy classes

The MMQ has been defined as a fixed value for all hydrogen application whereas it was a function of the mass flow rate for the compressed gas fuel. It is stated in OIML R139:2018 that the maximum MMQ for all types of HRS is **1 kg**.

3. For any quantity of the measurand equal to or greater than 1000 scale intervals of the meter (in gram), the repeatability of the flow meter error and the measuring system must be 2/3 of the MPE (1.5.4.11). As an example, for a meter with a resolution of 1 g, the repetability error of the flow meter should not exceed the values in the below:

Class	MMQ	MPE	Repeatability error	class	MMQ	MPE	Repeatability error
class 2	no	2%	1,33%	class 4	no	2%	2,67%
	yes	4%	2,67%		yes	4%	5,33%

Table 3: Repeatability errors

The calculation for the repetability error is based on this statement of the OIML R139:2018: “difference between the largest and the smallest results of the several successive measurements of the same quantity carried out under the same *repeatability condition.*”

Primary standard design for hydrogen flow meter calibration

Technical specifications

OIML R139:2018 and SAE J2601:2020 are the two relevant documents that drive the design and performances of the primary test bench. The main technical specifications of a primary standard for hydrogen flow meters are given below

- Mass flow rate range: (0.5 to 3.6) kg/min,
- Gas pressure range: (300 to 700) bar,
- Gas temperature range: (-40 to 40) °C,
- Fluid: hydrogen,
- Static calibration points: 5 mass flow rates (3 repetitions).

Mass flow rate shall be stable and variable on demand. The latter option shall reproduce HRS operating conditions. There shall be the possibility of performing transient temperature measurements where the tubing of the flow meter is at another temperature as the gas temperature at the start of the measurement. The test rig can be either a closed loop system, where hydrogen is reused, or an open loop system, where hydrogen is ejected in the atmosphere.

Measurement method and design

The primary standard could be either a gravimetric system or a PVT system. In the gravimetric method, the dispensed mass is determined by weighing the amount of delivered hydrogen in a high-pressure vessel on a scale. In the Pressure-Volume-Temperature (PVT) method, the dispensed mass is determined by measuring pressure and temperature of the collected gas in a known volume and then converting to mass using the density of the gas. Every method has its advantages and drawbacks. In this document, the gravimetric method will be developed because quite some knowledge has been collected during the MetroHyVe project on this method.

The primary test rig would consists of building blocks with each its specific use:

- low pressure storage: source of hydrogen at 200 bar
- compression stage: compresses hydrogen to high pressure (900 bar).
- high pressure storage: source of hydrogen at 900 bar
- heat exchanger: control gas temperature in the range of -40 °C to 40 °C.
- flow regulation unit: piping / valve to control the mass flow rate for meter calibration
- fast switching line: allows fast switching between stabilization / exhaust line to weighing line
- exhaust line: line used during stabilization of the main physical parameters
- weighing line: line leading to the weighing zone
- high pressure storage: collection of the hydrogen in the weighing zone
- high precision weighing device.

All these blocks need to be dimensioned to cover the specifications. Ideally, it should be a close looped system to limit the amount of hydrogen rejected in the atmosphere. A simplified P&ID of the primary test rig is sketched in Figure 2. It must be understood that not all valves are drawn.

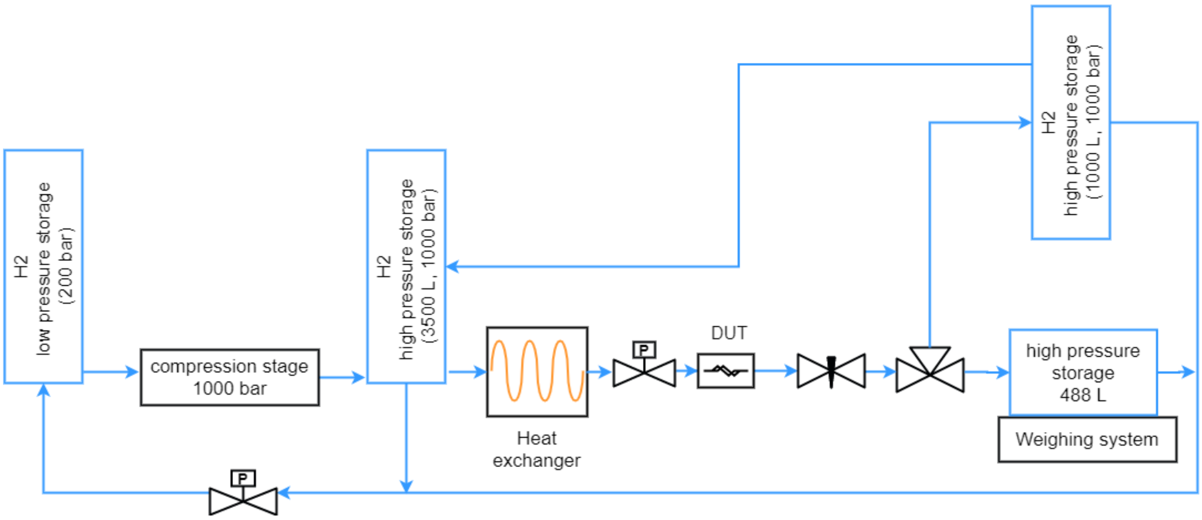

Figure 2: Piping and instrumentation diagram for the primary test rig for high-pressure calibration.

Hydrogen is stored in a low-pressure storage at 200 bar then compressed up to 900 bar in a high-pressure storage. This will serve as the source of hydrogen. Gas temperature can be adjusted by a heat exchanger that must be designed to achieve the SAEJ 2601:2020 requirements. A pressure control valve allows regulating the incoming pressure before the Device Under Test (DUT) between 300 bar and 700 bar while stable mass flow rate is adjusted through a needle valve. During mass flow rate adjustment, flow is guided through a temporary high-pressure storage tank. After the desired mass flow rate is obtained, flow is diverted through a three-way valve into a high-pressure tank placed on a weighing system where the hydrogen is collected. At the end of the measurement, flow is again diverted to the temporary storage tank before the next measurement starts.

Dimensioning of the components

The dimensions of the components are defined by the calibration procedure. As an example, we consider a 5 point calibration with 3 repetitions at (100, 50, 25, 15, 10) % of a maximum flow rate of 3.6 kg/min with a minimum collected mass of hydrogen of 1 kg or 45 s of measuring time. This yields the following minimum quantities of hydrogen or measuring times:

Flow rate (kg/min)	Measuring time (s)	Collected mass (kg)	Total collected mass (kg)
3.6	45	2.7	8.10
1.8	60	1.8	5.40
0.9	90	1.35	4.05
0.54	120	1.08	3.24
0.36	180	1.08	3.24

PID of the primary standard test rig

Ideally, it is a closed-loop system to limit the amount of hydrogen rejected in the atmosphere. The maximum amount of hydrogen needed to perform a mass flow meter calibration for static flow rate has been estimated to be around 30 kg (stabilization 45 seconds + acquisition). Figure 3 shows the calculation.

Mass flow meter calibration (D.U.T)											
Calibration routine	Wishes Pressure for calibration	max mass flow H2	Mass flow rate 100% (45s)	Mass flow rate 50% (60s)	Mass flow rate 25% (90s)	Mass flow rate 15% (120s)	Mass flow rate 10% (180s)	stabilisation time	measurement for each mass flow rate	**Measurements number**	H2 consuption for the full run
index	BarA	kg/mn	kg/mn	kg/mn	kg/mn	kg/mn	kg/mn	mn	mn	0 = none	kg
TOTAL	700	3,6	3,60	1,80	0,90	0,54	0,36	0,75			**29,43**
1	700	3,6	3,60					0,75	0,75	3,00	**10,8**
2	700	3,6		1,80				0,75	1,00	3,00	**6,75**
3	700	3,6			0,90			0,75	1,50	3,00	**4,725**
4	700	3,6				0,54		0,75	2,00	3,00	**3,645**
5	700	3,6					0,36	0,75	3,00	3,00	**3,51**

Figure 3: Hydrogen consumption assessment for high-pressure calibration with static mass flow rate

The calibration procedure is composed of 5 measurements points over the full range of the mass flow rate for hydrogen refuelling station (3.6 kg/min).

To reduce the size of the high-pressure buffer, the calibration will be done in 3 sequences. The compressor unit will have to work to pressurize the HP buffer at a required value during the calibration sequence. Figure 4 presents the proposed sequence.

Mass flow meter calibration (D.U.T)											
Calibration routine	Wishes Pressure for calibration	max mass flow H2	Mass flow rate 1	Mass flow rate 2	Mass flow rate 3	Mass flow rate 4	Mass flow rate 5	stabilisation time	measurement for each mass flow rate	**Measurements number (1 + repetition)**	H2 consuption for the full run
index	BarA	kg/mn	kg/mn	kg/mn	kg/mn	kg/mn	kg/mn	mn	mn	0 = none	kg
TOTAL	700	3,6	3,60	1,80	0,90	0,54	0,36	0,75			**25,92**
1	700	3,6	3,60					0,75	0,75	3	**10,8**
2	700	3,6		1,80				0,75	1,00	3	**6,75**
3	700	3,6			0,90			0,75	1,50	3	**4,725**
Compression Unit from 800 to 826 bar (estimated time = 30 min) at 187 Nm3/h											
4	700	3,6				0,54		0,75	2	3	**3,645**
Compression Unit from 795 to 822 bar (estimated time = 30 min) at 187 Nm3/h											
5	700	3,6					0,36	0,75	3	3	**3,51**

UPSTREAM H2 high pressure buffer							
Volume	intial H2 pressure	Temp H2 (intial or end of seq)	Rho H2 (initial seq state)	Mass H2 initial seq state	Ro H2 <<-- end of test seq	Mass H2 end of test seq	Pressure H2 end of seq test
m3	BarA	°C	kg/m3	kg	kg/m3	kg	BarA
3,5	1000	20	49,91	174,7	42	145,3	748
3,5	1000	20	49,91	174,7	47	163,9	899
3,5	899	20	46,70	163,4	45	156,7	839
3,5	839	20	44,74	156,6	43	151,9	800
Compression Unit from 800 to 826 bar (estimated time = 30 min) at 187 Nm3/h							
3,5	826	20	44,29	155,0	43	151,4	795
Compression Unit from 795 to 822 bar (estimated time = 30 min) at 187 Nm3/h							
3,5	822	20	44,14	154,5	43	151,0	791

Figure 4: Calibration sequence with compression needed to get enough hydrogen

It means that the high-pressure buffer must be large enough to maintain the pressure above 700 bar after the calibration procedure. The initial pressure must be higher than 700 bar to end around 700 bar (desired calibration pressure). The calculation (see Figure 5) shows that the volume and the pressure of the high-pressure buffer must be at least 3.5 m^3 at 1000 bar with some pause during the calibration. The choice to reduce the high-pressure buffer from 5 m^3 to 3.5 m^3 (with pause) is directly linked to the price of a cubic meter of storage at 1000 bar (~ 100 k€/m^3).

UPSTREAM H2 high pressure buffer							
Volume	intial H2 pressure	Temp H2 (intial or end of seq)	Rho H2 (initial seq state)	Mass H2 initial seq state	Ro H2 <<-- end of test seq	Mass H2 end of test seq	Pressure H2 end of seq test
m3	BarA	°C	kg/m3	kg	kg/m3	kg	BarA
5	1000	20	49,91	249,5	42	209,3	756
3,5	1000	20	49,91	174,7	38	134,5	**666**

Figure 5: High-pressure buffer requirement for static mass flow rate calibration – top: full calibration without compression, bottom: proposed configuration with 3 hours compression for the full calibration

If 3.5 m^3 of hydrogen at 1000 bar are required, 20 bundles of 18 B50 H_2 bottles (see Figure 6 below) are needed.

Volume B50	0,05 m^3
NB	18
Nb rack	20
Volume	18
Pressure	200
P x V	3600

Figure 6: H_2 bundles needed for high-pressure calibration of mass flow meter at 700 bar.

The heat exchanger must be designed to achieve the SAEJ 2601:2020 requirements. The gas temperature could be in the range of -40 °C to 40 °C. The mass flow meters will most likely be calibrated at -40 °C.

The high-pressure buffer after the 3-way valve has been designed to be around 1 m^3 and will contain approximately 50 kg of H_2 at 1000 bar. This buffer will be used during the stabilization period. This buffer will then be either re-injected in the 3.5 m^3 HP buffer (if pressure in the 3.5 m^3 buffer allows for it) or re-injected in the H_2 bundles at 200 bars. It is the needed capacity for the full calibration of the flow meter. The capacity should be large enough to realise the mass flow meter calibration.

The primary standard will be a weighing system with an expanded uncertainty lower than 0.3% for 1kg of H_2. Type 4 tanks are selected to reduce the weight of the system. Indeed, a 600 kg scale should be enough to measure the amount of dispensed hydrogen for a mass flow meter calibration.

As a reminder, the total amount of hydrogen for one calibration has been estimated to be around 40 kg. Five type 4 tanks of 104 L can contain up to 28.9 kg of H_2 at 950 bar (T=-40°C) for a weight of 80 kg per tank. This implies that the tanks need to be vented during the calibration procedure after the third and fourth mass flow rates (*i.e.*: 0.9 kg/min (3 times), vent, 0.54 kg/min (3 times), vent) with the compression unit working during venting. Figure 7 below presents a sequence of test for the type 4 tank.

DOWNSTREAM H2 high pressure buffer									
intial H2 pressure	Temp H2 (intial or end of seq)	Rho H2 (initial seq state)	Mass H2 initial seq state	Rho H2 <<-- end of test seq	Rho H2 for H2 max in reservoir	Rho H2 <<-- end of seq (can be from max)	H2 Mass can be received during seq	Mass H2 end of test seq	Pressure H2 end of seq test
m3	BarA	°C	kg/m3	kg	kg	kg/m3	kg	kg	BarA
0,52	1	-40	0,00	0,0	46,4	46	24,1	24,1	700,0
0,52	1	-40	0,00	0,0	46,4	21	24,1	10,8	234,5
0,52	235	-40	20,75	10,8	46,4	34	13,3	17,5	435,2
0,52	435	-40	33,61	17,5	46,4	43	6,6	22,2	613,7
Defueling the type 4 tank from 613 to 485 bar (estimated time = 30 min at 2 g/s)									
0,52	485	-40	36,33	18,9	46,4	43	5,2	22,5	628,8
Defueling the type 4 tank from 628 to 485 bar (estimated time = 30 min at 2 g/s)									
0,52	485	-40	36,33	18,9	46,4	43	5,2	22,4	623,0

Figure 7: Fuelling and venting of the receiving type 4 tank during high-pressure calibration

Calibration sequence and duration

As an example, the Figure 8 below presents a sequence of calibration for 5 points over the full mass flow range with 3 repeatability points. If the compressor can go up to 182 Nm^3/h during the compression and the venting is lower than 4.8 bar/min, the estimated time is 1.2 hours for the calibration (+ 4 hours to get back to the initial state).

TIME (Hr)	TIME (min)	TIME (SEC)	WHAT	CONDITION	MASS FLOW	PRESSURE TANK	PRESSURE RECEIVER
0,00	0,00	0	P1R1	START	0	1000	1
0,01	0,75	45	P1R1	UNSTABLE TO STABLE	3,6	973	51
0,03	1,50	90	P1R1	ACQUISITION	3,6	947	107
0,04	2,25	135	P1R2	ACQUISITION	3,6	923	168
0,05	3,00	180	P1R3	ACQUISITION	3,6	899	234
0,06	3,75	225	P2R1	UNSTABLE TO STABLE	1,8	884	269
0,08	4,75	285	P2R1	ACQUISITION	1,8	869	320
0,10	5,75	345	P2R2	ACQUISITION	1,8	854	375
0,11	6,75	405	P2R3	ACQUISITION	1,8	839	435
0,13	7,50	450	P3R1	UNSTABLE TO STABLE	0,9	832	457
0,15	9,00	540	P3R1	ACQUISITION	0,9	821	506
0,18	10,50	630	P3R2	ACQUISITION	0,9	811	558
0,20	12,00	720	P3R3	ACQUISITION	0,9	800	613
0,20	12,00	720	--	COMP / DEFUEL	0	800	613
0,70	42,00	2520	--	COMP / DEFUEL	0	826	485
0,71	42,75	2565	P4R1	UNSTABLE TO STABLE	0,54	821	499
0,75	44,75	2685	P4R1	ACQUISITION	0,54	813	540
0,78	46,75	2805	P4R2	ACQUISITION	0,54	804	583
0,81	48,75	2925	P4R3	ACQUISITION	0,54	795	628
0,81	48,75	2925	--	COMP / DEFUEL	0	795	628
1,31	78,75	4725	--	COMP / DEFUEL	0	822	485
1,33	79,50	4770	P5R1	UNSTABLE TO STABLE	0,36	817	493
1,38	82,50	4950	P5R1	ACQUISITION	0,36	808	534
1,43	85,50	5130	P5R2	ACQUISITION	0,36	800	577
1,48	88,50	5310	P5R3	ACQUISITION	0,36	791	623
1,48	88,50	5310	--	COMP / DEFUEL	0	791	623
5,48	328,50	19710	--	COMP / DEFUEL	0	1000	1

Figure 8: Sequence of mass flow meter calibration at high pressure

Uncertainty budget assessment

The relative calibration errors are key test results to ensure that HRSs comply with the maximum permissible error (MPE) requirements for type evaluations and verifications [1]. The relative calibration error in percent err_{H2} can be calculated by the following formula:

$$err_{H2} = \left(\frac{m_{EUT}}{m_{ref}} - 1\right) \times 100$$

where m_{EUT} is the dispensed mass on the equipment under test (EUT) which are readings of the HRS meter and m_{ref} is the dispensed mass which is calculated for the hydrogen field test standard (HFTS). The dispensed mass on the EUT m_{EUT} can be calculated by the following formula:

$$m_{EUT} = m_{EUT2} - m_{EUT1}$$

where m_{EUT1} is the initial dispensed mass reading and m_{EUT2} is the final dispensed mass reading on the HRS. The dispensed mass on the HFTS m_{ref} has recently been described in detail [2] and can be calculated by the following formula:

$$m_{ref} = (W_2 - W_1)\left(1 - \frac{\rho_0}{\rho_N}\right) + V_0[\rho_{air2}(1 + \lambda\Delta P_2)(1 + 3\alpha\Delta T_2) - \rho_{air1}(1 + \lambda\Delta P_1)(1 + 3\alpha\Delta T_1)] + V_{frame}(\rho_{air2} - \rho_{air1})$$

where W_1 is the initial and W_2 is the final scale reading with the mass correction factor $\left(1 - \frac{\rho_0}{\rho_N}\right)$. The buoyancy correction consists of two parts: 1) the external tank volume which is corrected for pressure and thermal expansion and 2) the frame placed on the scale.

Main Influence Factors

The main sources of measurement uncertainty have been considered with respect to the relative calibration error of mass flow meters (CMFs), which are used at HRSs calibrated with gravimetric approach using the HFTS. Table 4 give an overview of an example measurement and the resulting uncertainty budget.

input quantity		estimate		standard uncertainty		
	X_i	x_i	Unit	$u(x_i)$	Unit	contribution
Initial dispensed mass reading on EUT	m_{EUT1}	0,000	kg	0,00	%	0,0%
Final dispensed mass reading on EUT	m_{EUT2}	1,000	kg	0,21	%	86,5%
Initial scale reading	W_1	500,000	kg	0,05	%	4,4%
Final scale reading	W_2	501,000	kg	0,05	%	4,4%
Air density at reference condition	ρ_0	1,2	kg/m³	0,00	%	4,47E-07
Stainless steel density at ref. conditions	ρ_N	8000	kg/m³	0,00	%	4,47E-07
Hydrogen tank external volume	V_0	0,1200	m³	0,010	%	0,19%
Frame Volume	V_{frame}	0,070	m³	0,005	%	0,05%
Initial air density	ρ_{air1}	1,140	kg/m³	0,032	%	2,1%
Final air density	ρ_{air2}	1,150	kg/m³	0,033	%	2,2%
Initial pressure difference from ref. value	ΔP_1	0,10	MPa	0,000	%	3,60E-06
Final pressure difference from ref. value	ΔP_2	35,00	MPa	0,000	%	3,66E-06
Pressure expansion coefficient	λ	2,20E-04	MPa⁻¹	0,011	%	0,22%
Initial temperature difference from ref. value	ΔT_1	20,0	°C	0,000	%	2,68E-09
Final temperature difference from ref. value	ΔT_2	100,0	°C	0,000	%	2,77E-09
Linear thermal expansion coefficient	α	2,00E-06	°C⁻¹	0,000	%	8,03E-13
			(k=1)	0,22	%	100,0%

Table 4: As an example: A typical calculation for the measurement uncertainty U(k=1) for the calibration of a HRS using HFTS gravimetric method with a nominal mass of 1.0 kg. A summary of the input values is given in this table.

1. Meter Resolution

The displayed mass reading on the HRS is limited by the CMFs scale interval. This uncertainty contribution can be neglected for the initial mass reading when the HRS is equipped with a zero-setting device. The meter resolution on an HRS is typically 1 gram. A value of ±0.001 kg (rectangular distribution) was assigned to the uncertainty budget.

2. Zero-point Stability

According to uncertainty guidelines the zero-point stability of the HRSs meter also need to be taken into account in the uncertainty budget for the relative calibration error [3]. Zero-point stability is a property of a CMF and corresponds to a reading offset that depends on pressure and temperature and has a greater influence at lower flow rates. It largely determines the minimum flow rate at which a CMF can provide accurate measurements. Typical vehicle tank size is 100 liters for a NWP of 700 bar. It can hold approximately 4 kg of hydrogen, and with a typical refulling time of 5 minutes this gives an average mass flow rate of $\frac{4\,kg}{5\,min} = 0.8\,kg/min$.

In the course of these experiments, typical zero-point values of ±0.002 kg/min have been assigned. If one relates this value to the average mass flow rate value of 0.8 kg/min, this yields a maximum uncertainty of 0.25% due to zero-point stability. A value of ±0.002 kg was assigned to the uncertainty budget.

3. Scale Resolution

The scale reading on the HFTS is limited by the scale interval. The scale used on a HFTS typically has a resolution of 0.5 gram. A conservative value of ±0.005 kg was assigned to the uncertainty budget.

4. Scale Calibration Uncertainty

The calibration is performed to determine or verify the accuracy of the HFTSs scale, with an associated uncertainty. A value of ±0.0005 kg was assigned to the uncertainty budget.

5. Scale Calibration Deviation

The deviation describes how close the reading of the meter is to its calibration curve. A value of ±0.0005 kg was used in the uncertainty budget.

6. Scale Repeatability

Repeatability is a quantitative measure of how well a measuring device provides the same output when the measured parameter and conditions are held constant. Ideally, the measuring device will provide identical readings until the measured parameter is changed. However, all measuring devices will produce a spread of results to some degree. In order to assess repeatability, the measurement conditions must be kept as consistent as possible, by following the same measurement procedure with the same operators, using the same measurement system, at the same location with the same environmental conditions. Replicated measurements should be taken over a short period of time.

The repeatability of the scale can be expressed as a relative value from the actual calibration value. A value of ±0.0002 kg has been estimated for the uncertainty budget.

7. Scale Drift

The scale reading varies over time. For these measurements, a scale drift of 0.4 gram has been observed over a time of 90 minutes. Therefore, a value of ±0.0004 kg was assigned for the uncertainty budget.

8. <u>Air Density</u>

Air density depends mainly on pressure, temperature and humidity. It is important that the ambient conditions (e.g. heating from sunlight) are stable during tests. The air density has been has determined with a relative uncertainty of 0.15 % (k=1) during measurements. A value of ±0.0017 kg was assigned for the uncertainty budget.

Cost assessment

In this section, the cost assessment will not be done with full quotation received from manufacturers. This estimation needs to be taken with caution and price can vary significantly depending on the country for example.

Cost assessment for:				
INFRASTRUCTURE H2 - Primary test bench				
			1 357 500	**Estimation**
Désignation	Qté	P.U	montant	
		EUR HT	EUR HT	estimation or quotation
High pressure compressor	1,00	300 000,00	**300 000**	quotation
Heat Exchanger T40 / 1000bar	1,00	120 000,00	**120 000**	estimation
High pressure BufferH2 upstream 3500 L / 1000 bar	1,00	350 000,00	**350 000**	quotation
3 way valve	1,00	15 000,00	**15 000**	estimation
Type 4 - 104L	5,00	8 000,00	**40 000**	quotation
Frame for type 4 tank	1,00	7 500,00	**7 500**	estimation
Pressure relief valve	1,00	5 000,00	**5 000**	estimation
High pressure Buffer H2 downstream 1000L / 1000 Bar	1,00	100 000,00	**100 000**	quotation
H2 return pressure regulator	1,00	5 000,00	**5 000**	estimation
Empty Buffer(B50L - 200 bar)	1,00	50 000,00	**50 000**	estimation
SKID & piping (1000 bar / 50 bar)	1,00	60 000,00	**60 000**	estimation
Scale (500 kg)	1,00	15 000,00	**15 000**	quotation
valves	10,00	3 000,00	**30 000**	estimation
Sensors	10,00	3 000,00	**30 000**	estimation
Ex electonic hardware	1,00	75 000,00	**75 000**	estimation
Acquisition system / Operating software	1,00	50 000,00	**50 000**	estimation
H2 security	1,00	15 000,00	**15 000**	estimation
Audit	1,00	15 000,00	**15 000**	estimation
Building arrangement	1,00	25 000,00	**25 000**	estimation
piping insulation	1,00	50 000,00	**50 000**	estimation

The estimated cost (without ETP) is 1.4 M€.

Concluding remarks

In this document, we have presented specifications and a tentative design for a primary calibration test rig for hydrogen flow metering up to 900 bar and its associated uncertainty budget. Based on the design, a bill of material was created which led to a cost assessment. The estimated cost for developing a primary test rig for hydrogen flow metering up to 900 bar amounts to around 1.4 M€. This amount only covers the material needed for the test rig and does not take into account the needed infrastructure (building, parcel, technical requirements of the building …). Neither does it take into account the cost in man month for building the test rig. It can be safely said that such an investment is most probably beyond the capabilities of a single national metrology institute and that a consortium would need to be created to develop, build and run such a test rig.

References

[1] "OIML R139: Compressed gaseous fuel measuring systems for vehicles Part 1: Metrological and technical requirements," International Organization of Legal Metrology, 2018.

[2] M. d. Huu, M. Tschannen, H. Bissig, P. Stadelmann, O. Büker, M. MacDonald, R. Maury, P. Neuvonen, H. Petter and K. Rasmussen, "Design of gravimetric primary standards for field-testing of hydrogen refuelling stations," vol. 73, no. Flow Measurement and Instrumentation, 2020.

[3] "OIML R139: Compressed gaseous fuel measuring systems for vehicles Part 2: Metrological controls and performance tests," International Organization of Legal Metrology, 2018.