Flow Measurements for Hydrogen Vehicle Refuelling

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Measurement Solutions for Energy Gases,

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Background

- Hydrogen vehicles are a potential alternative to battery electric vehicles for decarbonisation of transport

- The accuracy requirements for hydrogen refuelling station (HRS) dispensers are set out in the international recommendation OIML R139

- Challenging to achieve due to operating conditions at hydrogen refuelling stations, which are specified in the worldwide accepted standard SAE J2601

- OIML R139 does not say which testing equipment should be used, but flow standards have been developed by measurement institutes

5.2 Maximum permissible error (MPE)

5.2.1 Without prejudice to 5.2.3, the maximum permissible error on mass indications, positive or negative, is equal to the values presented in Table 1:

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

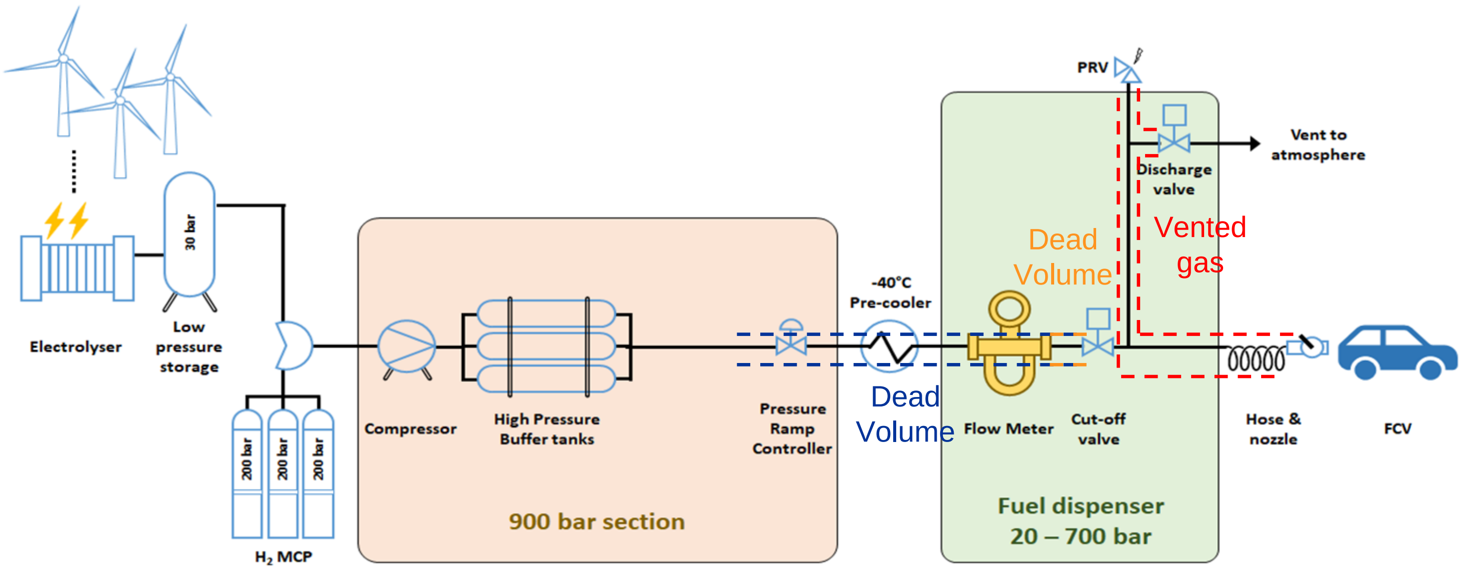
Note 1: National Authorities may decide whether subsequent verifications should be conducted and whether a different maximum permissible error should be applied for subsequent verification.

Note 2: "In service inspection" refers to an inspection at any moment within the period of time between verifications (refer to OIML D 16, 2.25).

Background

Considering the typical HRS, the main sources of measurement error/uncertainty are:

1. Accuracy of the flow meter
2. Gas vented at end of refuelling
3. Density changes in “dead volumes”



The various influences on the flow meter accuracy (incl. flow rate, temperature, pressure, density) were studied in detail in the first project. The other two influences can be calculated from PVT data.

Background

Significant progress was made in 16ENG01MetroHyVe towards providing traceability to HRS dispensers

- Surveys of HRS operators to understand the most common station configurations, operating conditions & uncertainty sources
- Developing primary standards that could be used for verifications, intercomparisons to demonstrate claimed uncertainty
- Extensive Testing on flow meters used in HRS
- Test campaigns at HRS

Background

METROLOGY for HYDROGEN VEHICLES 2

Open access publications are all accessible via:

- Flow Measurement & Instrumentation journal, Flomeko 2019 Special Edition
- MetroHyVe 2 website: https://www.sintef.no/projectweb/metrohyve-2/metrohyve1-resource/

Flow Measurement and Instrumentation 73 (2020) 101747

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: http://www.elsevier.com/locate/flowmeasinst

ELSEVIER

Design of gravimetric primary standards for field-testing of hydrogen refuelling stations

M. de Huu[a,*], M. Tschannen[a], H. Bissig[a], P. Stadelmann[b], O. Büker[c], M. MacDonald[d], R. Maury[e], P.T. Neuvonen[f], H.T. Petter[g], K. Rasmussen[h]

Flow Measurement and Instrumentation 74 (2020) 101743

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: http://www.elsevier.com/locate/flowmeasinst

ELSEVIER

Hydrogen refuelling station calibration with a traceable gravimetric standard

R. Maury[a,*], C. Auclercq[a], C. Devilliers[b], M. de Huu[c], O. Büker[d], M. MacDonald[e]

Flow Measurement and Instrumentation 76 (2020) 101815

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

ELSEVIER

Investigations on pressure dependence of Coriolis Mass Flow Meters used at Hydrogen Refueling Stations

Oliver Büker[a,*], Krister Stolt[a], Marc de Huu[b], Marc MacDonald[c], Rémy Maury[d]

Flow Measurement and Instrumentation 79 (2021) 101915

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: http://www.elsevier.com/locate/flowmeasinst

ELSEVIER

Calibration of hydrogen Coriolis flow meters using nitrogen and air and investigation of the influence of temperature on measurement accuracy

Marc MacDonald[a,*], Marc de Huu[b], Rémy Maury[c], Oliver Büker[d]

METROLOGY for HYDROGEN VEHICLES

REPORT:

A1.1.2: Public report on operating conditions and uncertainty sources of a Hydrogen Refuelling Station(HRS)

METROLOGY for HYDROGEN VEHICLES

Comparison report

A1.4.2: Intercomparison of gravimetric standards

METROLOGY for HYDROGEN VEHICLES

GOOD PRACTICE GUIDE:

Calibration and validation of flow meters used at HRSs for quantifying hydrogen dispensed into vehicles

METROLOGY for HYDROGEN VEHICLES

REPORT:

A1.5.5: Determination of the Overall Uncertainty Budgets of Different Calibration approaches for CFM and Assessment of their Suitability

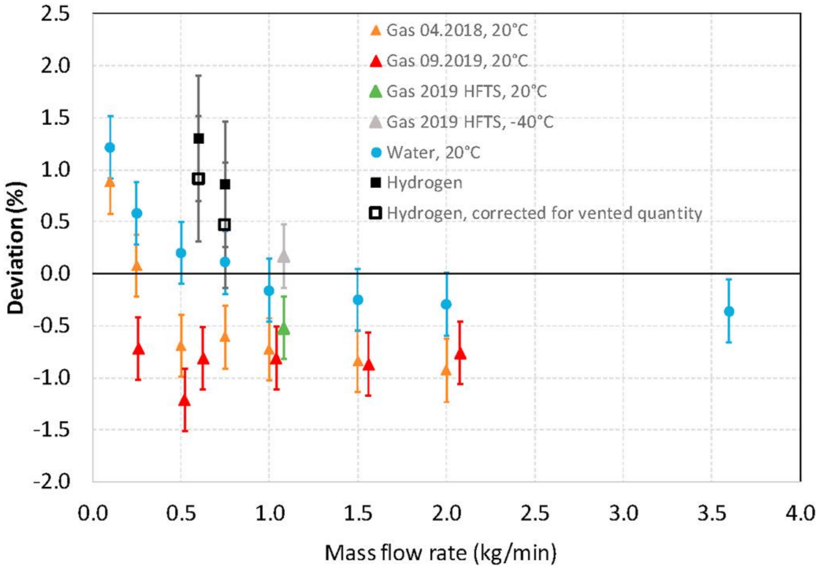
Background

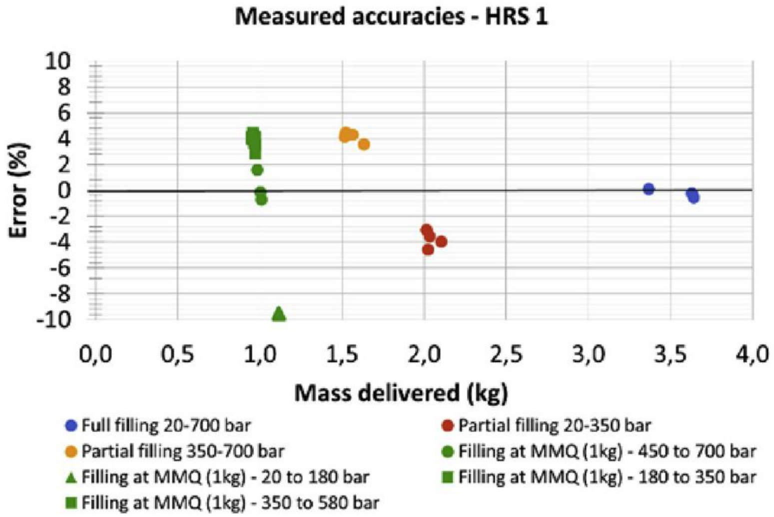
HRS dispensers are required to meet the OIML R139 accuracy requirements

- Accuracy Class 2 or Class 4 (2% or 4% MPE)

From the previous project we know:

- The available flow meters are capable of meeting the accuracy requirement
- Regardless, larger errors are observed at many stations
- This is largely a result of the station design e.g. when dead volume is large and no corrections are applied





Background

The continuation project, 19ENG04 MetroHyVe 2 builds on the work of the first project:

WP1: Flow Metering

- New primary standards for light-duty vehicles
- New primary standards for heavy-duty vehicles
- Secondary flow standards for faster verifications of dispensers
- Measurement uncertainty tool for HRS dispensers
- Recommendation for HRS verification periods

Dissemination of knowledge via reports, good practice guides, journal papers

Primary Standards (light-duty)

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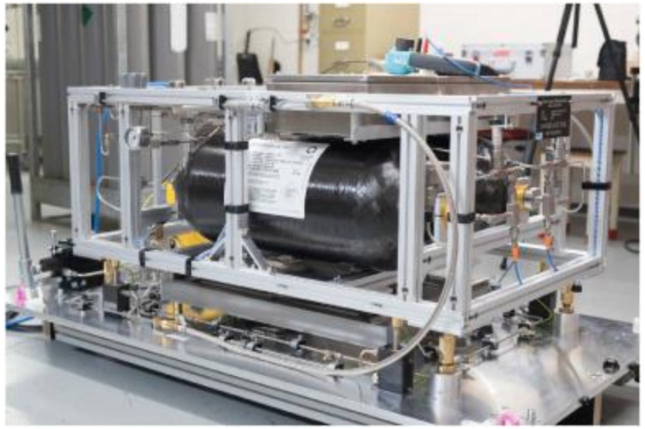
Several standards with the required uncertainty 0.3% (k=2)

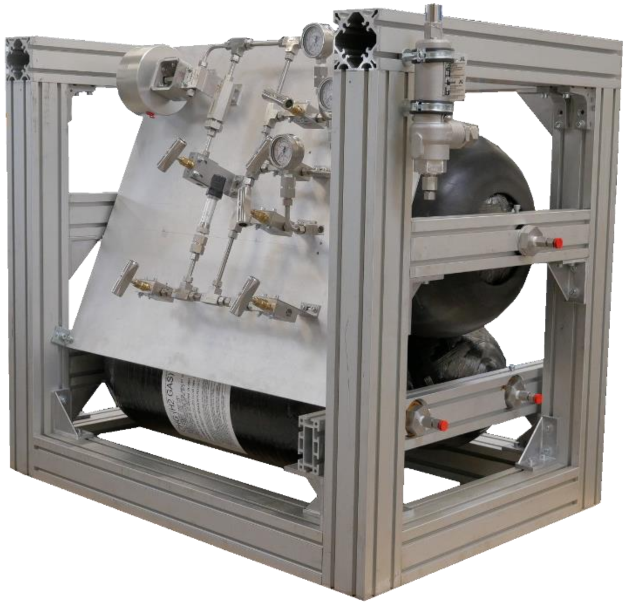
MetroHyVe 1

Institute	Tank volume
METAS	2 x 36 L
Justervesenet	3 x 36 L
VSL	3 x 52 L



MetroHyVe 2

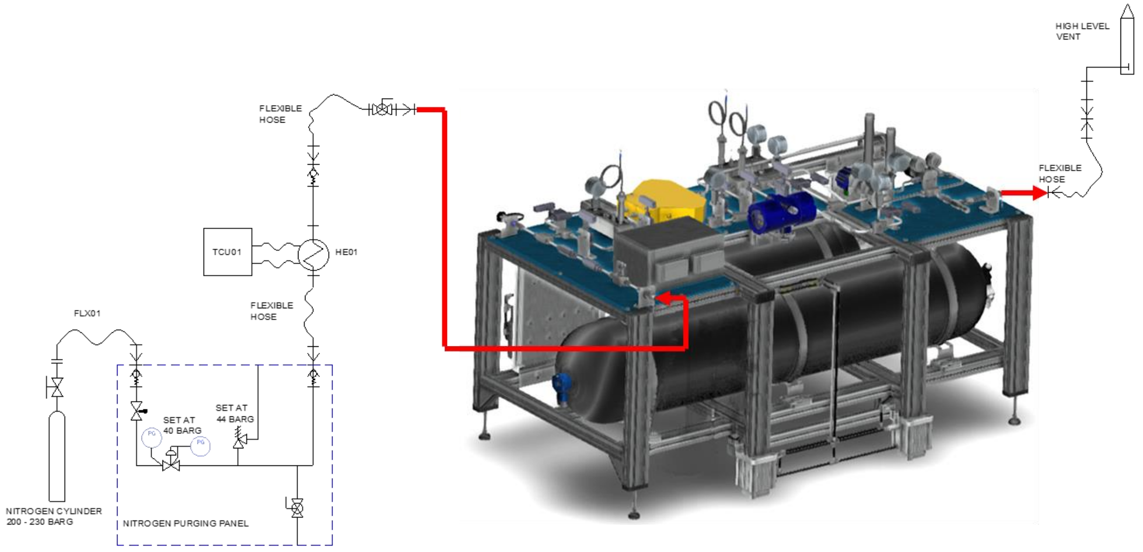
Institute	Tank volume
BEV-PTP	1 x 76 L, 2 x 36 L
CESAME	2 x 104 L
NEL	1 x 51 L, 1 x 103 L

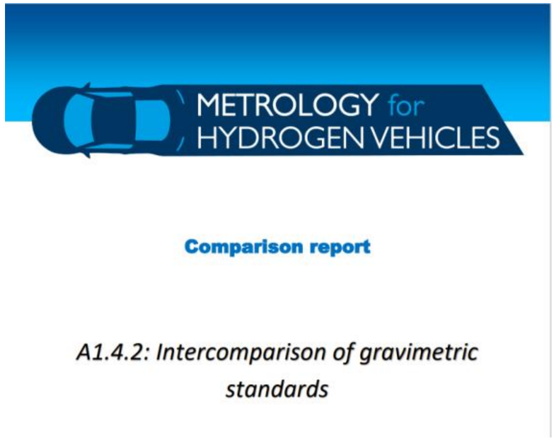


Primary Standards (light-duty)

In MetroHyVe 2, new primary standards are built

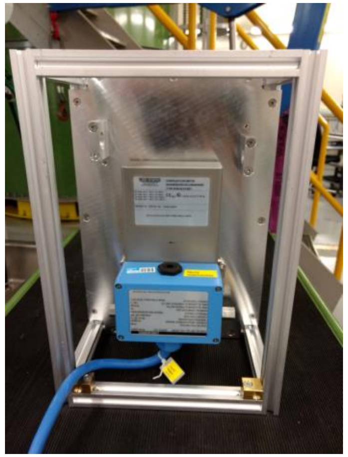
- Intercomparisons organised to validate the new flow standards, with some existing: METAS, JV, CESAME, NEL, BEV-PTP
- Intercomparisons carried out the same way as in MetroHyVe 1:
  - Fill the tanks with nitrogen to approx. 40 bar
  - Compare weigh-scale measurements with transfer standard flow meter




METROLOGY for HYDROGEN VEHICLES

Comparison report

A1.4.2: Intercomparison of gravimetric standards



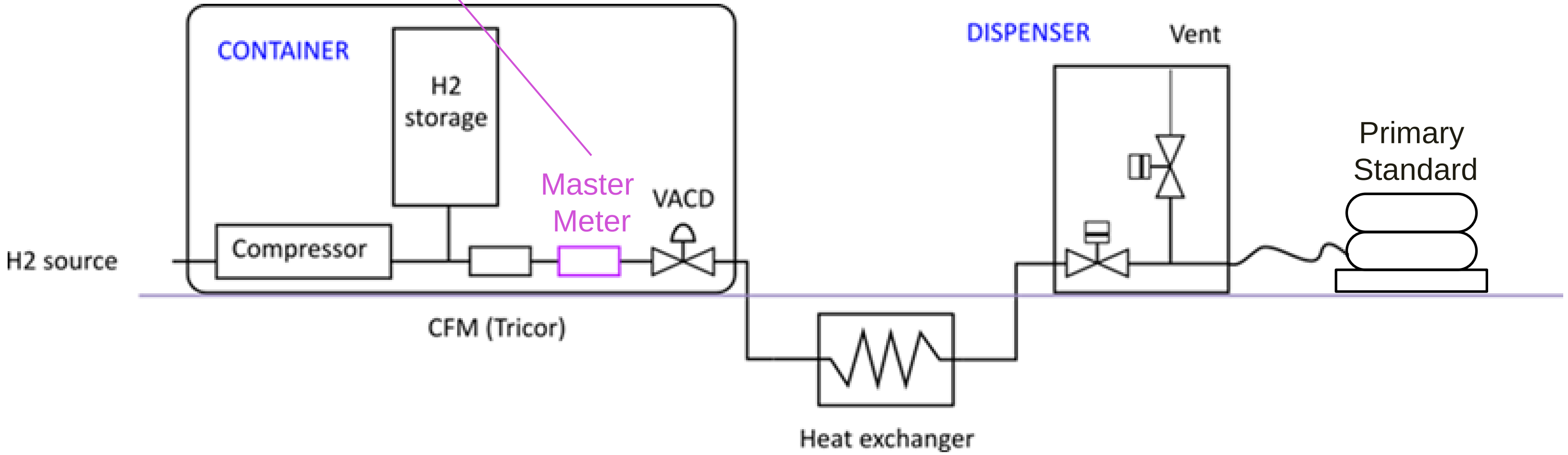
Primary Standards (light-duty)

The laboratory comparison is useful but has limitations

- Nitrogen less prone to leaks than hydrogen
- Pressure range limited to 40 bar, instead of 700 bar
- Does not account for outdoor environment (low ambient temperature, wind, rain, condensation/icing on tanks, vibration etc)

Field comparisons also organised at HRS

- Experimental HRS of project partner ZBT, Duisburg
- Transfer standard mounted in HRS, upstream of pre-cooler
- First measurements by CESAME and METAS in March



Primary Standards (heavy-duty)

- Existing primary standards have similar hydrogen capacity as light-duty vehicles (cars)
- Approx 4-6 kg H_2 at 700 bar
- When refilled at the HRS, filling times and flow rates same as for a car

This is not the case for heavy-duty vehicles (trucks)

- These vehicles typically store 30 kg+ hydrogen at 350 bar, with collection volumes ≥ 1000 L
- Light duty primary standards have 100 – 200 L collection vessels
- This leads to much lower flow rates when filling the primary standards compared to the vehicle ⇒ not a representative test of the station.

- METAS and NEL are building new primary standards for heavy-duty refuelling:

			H_2 Capacity		Average flow rate	
Institute	Pressure Class	Tanks	@ 350 bar	@ 700 bar	3 Mpa/min, no pre-cooling	20 Mpa/min
NEL	350 bar	3 x 350 L	25.2 kg	-	1.8 kg/min	-
METAS	700 bar	6 x 100 L	14.4 kg	24.5 kg	1.02 kg/min	6.8 kg/min

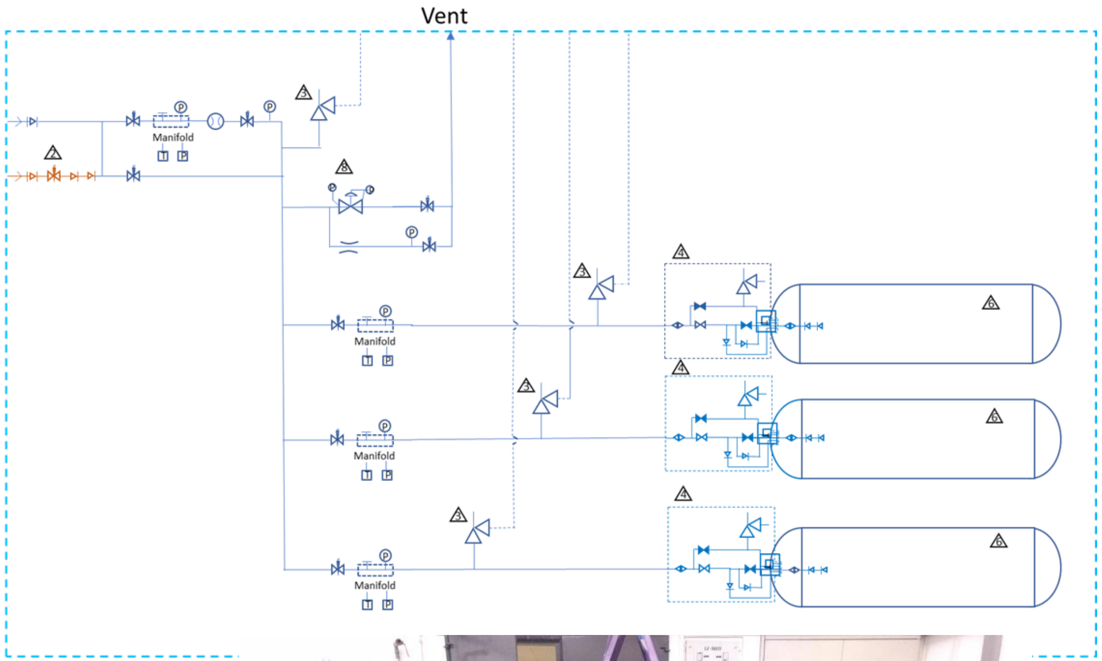
- Both systems are gravimetric, target measurement uncertainty is 0.5% (k=2) for 1 kg fill.

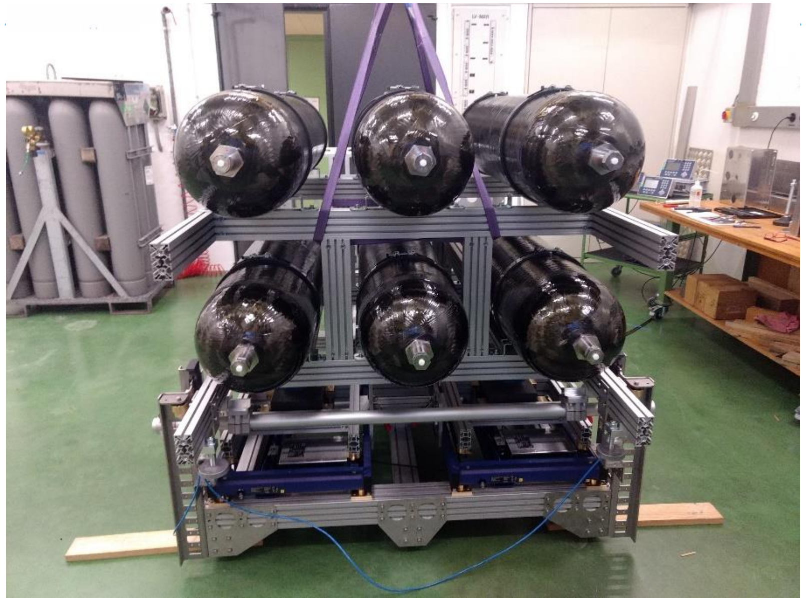
Primary Standards (heavy-duty)

- NEL design using 3 × 350 L tanks, total 24 kg H_2 capacity at 350 bar
  – Each tank will be weighed independently, 1 weigh scale for each tank
  – Small dead volumes must be vented before tanks are weighed, PVT corrections must be applied.

- METAS also using 3 weigh-scales, but the loads will be spread across all 3 scales simultaneously

- Both are under construction, completed in Q2 2023





Secondary standard

Although crucial, the portable primary standards have limitations:

- HRS verifications are time consuming
- Problems scaling up, practical limits are already reached for trucks

MetroHyVe 2 is investigating the use of secondary standards for HRS verifications

- CESAME developed HRSmsr: Hydrogen Refuelling Station mobile secondary reference

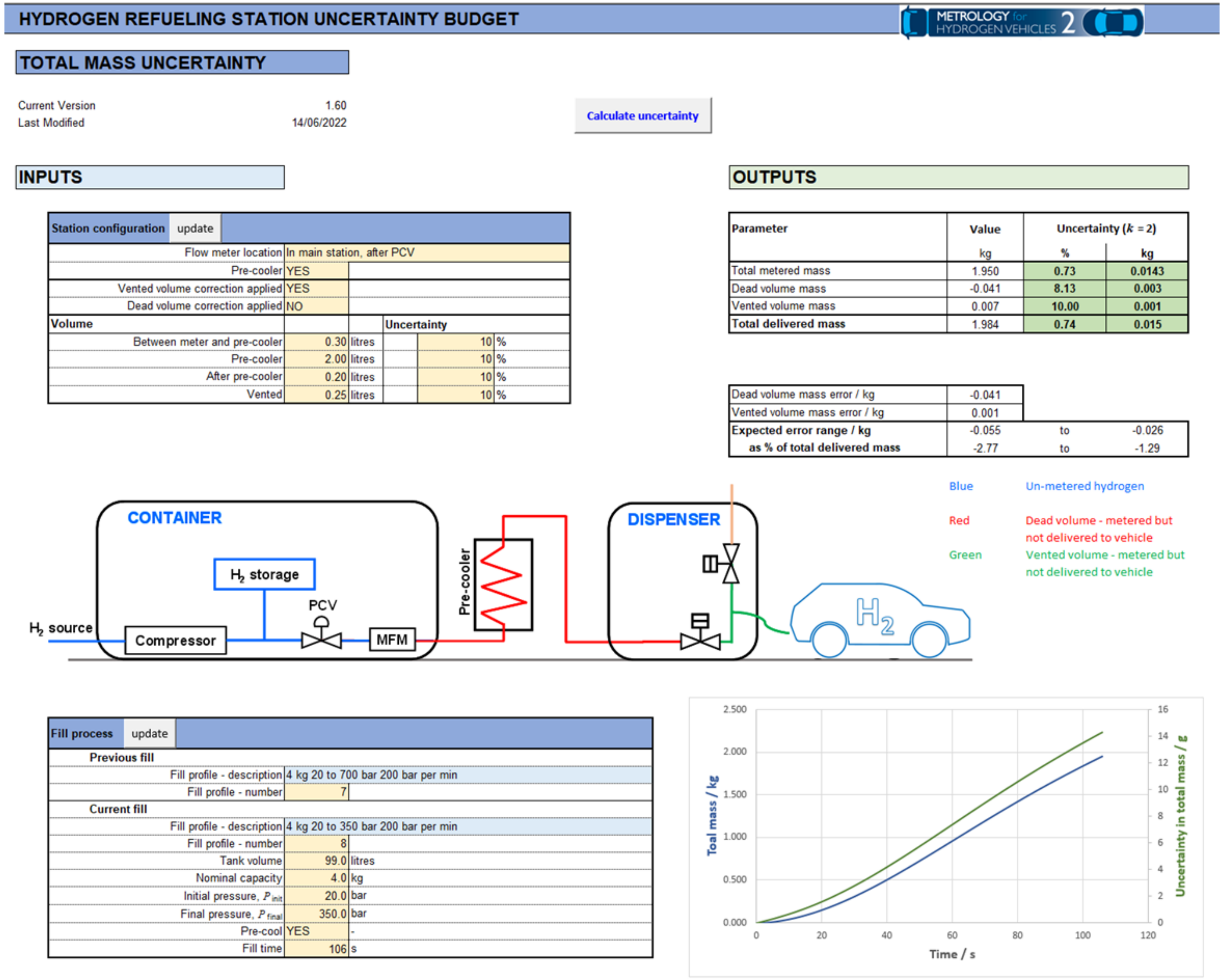
- SI traceability via CESAME primary standard, first ISO 17025 accredited primary reference (regarding OIML R-139) in Europe

- Claimed uncertainty < 0.5% (k=2)

- Initial and subsequent verifications (legal metrology) will be faster, cheaper, easier!

Measurement Uncertainty Tool

- Tool for HRS manufacturers, operators and notified bodies to understand uncertainty sources
- Using knowledge gained from MetroHyVe 1&2
- VBA-enabled Excel file
- Choices for station configuration affect the UI and calculations
- Calculates overall uncertainty of the flow meter and error range at dispenser
- Final version will be accessible from MetroHyVe 2 website



HYDROGEN REFUELING STATION UNCERTAINTY BUDGET

TOTAL MASS UNCERTAINTY

Current Version	1.60
Last Modified	14/06/2022

Calculate uncertainty

INPUTS

Station configuration	update			
Flow meter location	In main station, after PCV			
Pre-cooler	YES			
Vented volume correction applied	YES			
Dead volume correction applied	NO			
Volume			Uncertainty	
Between meter and pre-cooler	0.30	litres	10	%
Pre-cooler	2.00	litres	10	%
After pre-cooler	0.20	litres	10	%
Vented	0.25	litres	10	%

OUTPUTS

Parameter	Value	Uncertainty (k = 2)	
	kg	%	kg
Total metered mass	1.950	0.73	0.0143
Dead volume mass	-0.041	8.13	0.003
Vented volume mass	0.007	10.00	0.001
Total delivered mass	1.984	0.74	0.015

Dead volume mass error / kg	-0.041		
Vented volume mass error / kg	0.001		
Expected error range / kg	-0.055	to	-0.026
as % of total delivered mass	-2.77	to	-1.29

Fill process	update	
Previous fill		
Fill profile - description	4 kg 20 to 700 bar 200 bar per min	
Fill profile - number	7	
Current fill		
Fill profile - description	4 kg 20 to 350 bar 200 bar per min	
Fill profile - number	8	
Tank volume	99.0	litres
Nominal capacity	4.0	kg
Initial pressure, P_{init}	20.0	bar
Final pressure, P_{final}	350.0	bar
Pre-cool	YES	-
Fill time	106	s

Measurement Uncertainty Tool

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The user specifies:

- Location of flowmeter
- If corrections are applied for vented volume and dead volume
- Volumes for piping between the flow meter and the dispenser nozzle
- Filling process for current and previous user
- User can add new fill profile data
- Example fill profiles generated using NREL H2FillS software

INPUTS

Station configuration	update			
Flow meter location	In main station, after PCV			
Pre-cooler	YES			
Vented volume correction applied	YES			
Dead volume correction applied	NO			
Volume			**Uncertainty**	
Between meter and pre-cooler	0.30	litres	10	%
Pre-cooler	3.00	litres	10	%
After pre-cooler	3.00	litres	10	%
Vented	0.20	litres	10	%

Fill process	update	
Previous fill		
Fill profile - description	4kg 100 L tank, 35 to 700 bar with meter between PCV and cooler	
Fill profile - number	14	
Current fill		
Fill profile - description	4kg 100 L tank, 20 to 350 bar with meter between PCV and cooler	
Fill profile - number	4	
Tank volume	100.0	litres
Nominal capacity	4.0	kg
Initial pressure, P_{init}	20.0	bar
Final pressure, P_{final}	350.0	bar
Pressure ramp rate	200	bar min^{-1}
Precool	YES	
Fill time	113	s

Measurement Uncertainty Tool

METROLOGY for HYDROGEN VEHICLES 2

Flow meter uncertainty budget

- Takes fill profile data and station configuration
- Calculates flow meter uncertainty over refilling period

User can specify flow meter dependence on:

- Flow rate
- Pressure
- Temperature

Default values are based on MetroHyVe 1 findings

HYDROGEN REFUELING STATION UNCERTAINTY BUDGET

METROLOGY for HYDROGEN VEHICLES 2

MASS FLOW RATE UNCERTAINTY

Current Version 1.60
Last Modified 14/06/2022

INPUTS

Flow meter		
Calibration temperature, T_{cal}	20.0	°C
Calibration pressure, P_{cal}	20.0	bar
Calibration uncertainty	0.30	%
Repeatability	0.10	%
Reproducibility	0.50	%
Zero-point stability	0.000033	kg s^{-1}
Pressure effect	0.0001	% bar^{-1}
Temperature effect	0.000001	kg s^{-1} $°C^{-1}$
Long-term drift	0.020	% $year^{-1}$
Operating time	1	years
Fluid		
Temperature, T_{gas}	45.43	°C
Pressure, P_{gas}	374.30	bar
Flow rate, $\dot{m}$	0.019	kg s^{-1}

EXPANDED OUTPUT UNCERTAINTY (k = 2)

	%	kg s^{-1}
Uncertainty in mass flow rate	0.70	0.0001

Mass Flow Rate

															Enter either			
	Rank and Weighting	Uncertainty Source	Units	Value	Type	Expanded Uncertainty U	Input as	Absolute Expanded Uncertainty U	Distribution	Divisor k	Standard Uncertainty u	Sensitivity Coefficient c	Output Uncertainty $c.u$	Variance $(c.u)^2$	Relative Uncertainty of u	Degrees of Freedom ν	Degrees of Freedom ν	W-S Summation Terms
Inputs	2 - 18.2%	Calibration	kg s^{-1}	0.019	A	3.000E-01	Relative	5.606E-05	Normal (k=2)	2.00	2.803E-05	1	2.803E-05	7.857E-10			∞	0.000E+00
	5 - 2.0%	Repeatability	kg s^{-1}	0.019	A	1.000E-01	Relative	1.869E-05	Normal (k=2)	2.00	9.344E-06	1	9.344E-06	8.730E-11		10	10	7.622E-22
	1 - 67.2%	Reproducibility	kg s^{-1}	0.019	B	5.000E-01	Relative	9.344E-05	Rectangular	1.73	5.395E-05	1	5.395E-05	2.910E-09	0.10		50	1.694E-19
	3 - 6.4%	Zero-point stability	kg s^{-1}	0.019	B	3.333E-05	Absolute	3.333E-05	Normal (k=2)	2.00	1.667E-05	1	1.667E-05	2.778E-10	0.10		50	1.543E-21
	6 - 0.3%	Difference between P_{gas} and P_{cal}	kg s^{-1}	0.019	B	3.543E-02	Relative	6.621E-06	Normal (k=2)	2.00	3.310E-06	1	3.310E-06	1.096E-11	0.10		50	2.402E-24
	4 - 5.8%	Difference between T_{gas} and T_{cal}	kg s^{-1}	0.019	B	3.179E-05	Absolute	3.179E-05	Normal (k=2)	2.00	1.589E-05	1	1.589E-05	2.526E-10	0.10		50	1.276E-21
	7 - 0.1%	Long-term drift	kg s^{-1}	0.019	B	2.000E-02	Relative	3.737E-06	Normal (k=2)	2.00	1.869E-06	1	1.869E-06	3.492E-12	0.10		50	2.439E-25
Output			Units	Value		Relative Expanded Uncertainty U'		Absolute Expanded Uncertainty U	Distribution	Coverage Factor k	Standard Uncertainty u	Sensitivity Coefficient c	Output Uncertainty $c.u$	Variance $(c.u)^2$				Effective DoF ν_{eff}
		Overall Uncertainty	kg s^{-1}	0.019		**0.70**		**0.0001**	Normal (95%)	1.98	0.0001	1	6.579E-05	4.328E-09				108
						0.70		**0.0001**	Normal (k=2)	2.00								

Summary

MetroHyVe 1 established flow measurement traceability for hydrogen vehicles. This is further developed in MetroHyVe 2:

- More (light-duty) primary standards to enable verifications in their respective countries
- Validation via lab and field intercomparisons
- New (heavy-duty) primary standards for buses, trucks
- New secondary standard for faster, more efficient HRS verifications
- Guidance documents and measurement uncertainty tool

METROLOGY for HYDROGEN VEHICLES 2

This project “Metrology for Hydrogen Vehicles 2” (MetroHyVe 2) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme under Grant agreement No [19ENG04] .

THANK YOU