D4.3 Public report – results of the HyAC project

REPORT

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Acknowledgement

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Table of content

Introduction & scope

This document serves as a reporting for the deliverable D4.3 in the FCH-JU supported HyAC project and outlines the results of the project.

The overall scope of the HyAC project has been address the topic of legal metering for commercial hydrogen fuel dispensing.

The project has analyzed existing regulation for fuel metering and past experiences on hydrogen. This has been done for a range of selected countries, where construction of Hydrogen Refueling Stations (HRS) and roll-out of Fuel Cell Electric Vehicles (FCEV) is either ongoing or planned.

Boundary conditions for hydrogen mass flow meters when used for 70MPa have been developed based on technical analyses. The aim has been to provide mass flow meter suppliers with a better understanding of the operation environment in which the component is to be used at 70MPa Hydrogen Refueling Stations (HRS).

Within the hydrogen development efforts has also been conducted on optimizing existing hydrogen mass flow meter technology. In addition test equipment for mass flow meter accuracy has also been developed enabling verification at factory or in field at the HRS of the mass flow meter used.

1. Analysis of regulation for metering of fuel dispensing & experiences with hydrogen

1.1 OIML standard & MID directive – possible inclusion of hydrogen

Various existing OIML standards and MID directives for metering could act as a basis for considerations on hydrogen accuracy metering.

Table below outlines existing standards and directives for metering of various medias, and the accuracy requirement.

		Approval *		Verification
Document	Description	MPE System, ± %	MPE Meter, ± %	MPE ± %
OIML R139	**Compr. gaseous fuel M/S**	**1,5**	**1**	**2**
OIML R140	M/S for gaseous fuel	0,9 - 2		
MID MI-002	Gas Meters…		1 - 1,5 (2 – 3)	
MID MI-005	Liquids other than water	0,3 – 2,5	0,2 – 1,5	
OIML R81	Dyn M/S Cryogenic liquids	2,5	1,5	2,5
OIML R105	Direct Mass Flow liquids - when liquified gases	0,3 - 0,5 0,6 - 1		0,5 1
OIML R117	Liquids other than water - liquefied gases under pressure, temp < -10 ºC	0,5 – 1,5 1,5	0,3 – 1,0	
OIML R137	Gas Meters		0,5 – 1,5 (1 – 3)	1 – 3 (1 – 6)
CCR proposal	Proposed accuracy classes	2 – 10	1,5 – 5	2 – 10
* accuracy classes depending on application				

Hydrogen would most likely have to be added in the future as an ANNEX to one or several of the directives and/or standards.

Concerning adding hydrogen as an annex to MID and/or standard, this could be based on the OIML recommendations for the “model” national legislation.

During the period that the project work in the HyAC project has been on-going, the OIML R139 has been split in to sub-documents and updated to include also Hydrogen. This is excellent as such, as there will be normative documents available to refer to in national legislations. The HyAC project has however not been in a position to influence the technical contents, which has not been adapted for hydrogen, i.e. the same MPE (maximum permissible error) applies for Hydrogen as for other gases. No consideration is thus taken for the stabile energy content of hydrogen. Neither is any adapted procedure specified, e.g. adapted pressure level when starting measurement.

OIML R139 – Compressed gaseous fuel measuring systems for vehicles
This Recommendation applies to measuring systems intended for the refueling of motor vehicles, small boats, and aircraft with compressed natural gas, hydrogen, biogas, gas blends or other compressed gaseous fuels. They may also be applicable to other vehicles, for instance trains. The MPE of mass indication is +/- 2 % at verification. At approval the MPE is +/- 1,5% for the system (+/- 1% for the meter). This is independent of gas, i.e. the same for hydrogen as for e.g. CNG. Re-verification period if applied, is set to 5 years.

Other OIML documents that can be of interest concerning the structure and content are e.g.:

OIML R140 - Measuring systems for gaseous fuel
This Recommendation applies to measuring systems for gaseous fuel: with a designed maximum flowrate Qmax equal to or greater than 100 m3/h at base conditions and for operating pressures equal to or greater than 200 kPa (2 bar) absolute. This recommendation includes:

- Metrological requirements
  Accuracy classes
  Maximum permissible errors (MPE)
- Technical requirements
  Rated operating conditions
  Ancillary devices
  Indications
- Markings
- Sealing
- Type evaluation tests
  Test procedures
- Initial verification
- Subsequent verification

OIML R137 - Gas meters
This Recommendation applies to gas meters based on any measurement technology or principle that is used to measure the quantity of gas that has passed through the meter at operating conditions. The quantity of gas can be expressed in units of volume or mass. This Recommendation applies to gas meters intended to measure quantities of gaseous fuels or other gases. It does not cover meters

used for gases in the liquefied state, multi-phase, steam and compressed natural gas (CNG) used in CNG dispensers. This recommendation includes:

- Metrological requirements
  Rated operating conditions
  Accuracy classes and maximum permissible errors (MPE)
- Technical requirements
  Construction
  Ancillary devices
  Power sources
- Inscriptions
  Markings and inscriptions
- Sealing
  Verification marks and protection devices
- Type evaluation tests
  Test procedures
  Initial verification and subsequent verification

1.2 Experiences with hydrogen metering in selected countries

1.2.1 United Kingdom

There is currently no national legislation for the measurement of Hydrogen, as a gas, in the UK. Measuring instruments concerned with the measurement of Hydrogen as a liquid would be subject to UK Statutory Instrument 2006 No. 1266 The Measuring Instruments (Liquid Fuel and Lubricants) Regulations 2006 which implement into UK legislation the requirements of Directive 2004/22/EC of the European Parliament and of the Council of 31st March 2004 on measuring instruments relating to ANNEX MI-005 Measuring Systems for the Continuous and Dynamic Measurement of Quantities of Liquids other than Water.

Subject to certain limitations (in the Regulations) , these Regulations apply to a measuring system which is— (a) for use for trade* in the making of a continuous and dynamic measurement of liquid fuel in a quantity equal to or less than 100 litres or 100 kilograms; and first placed on the market or put into use on or after 30th October 2006.

These regulations define the maximum permissible errors dependent upon the designated accuracy class.

***Note :** "use for trade" is defined in the UK Primary legislation – Weights and Measures Act 1985 CHAPTER 72, 7 Meaning of "use for trade":

1. In this Act "use for trade" means, subject to subsection (3) below, use in Great Britain in connection with, or with a view to, a transaction falling within subsection (2) below where-
    a. the transaction is by reference to quantity or is a transaction for the purposes of which there is made or implied a statement of the quantity of goods to which the transaction relates, and
    b. the use is for the purpose of the determination or statement of that quantity.

2. A transaction falls within this subsection if it is a transaction for—
    a. the transferring or rendering of money or money's worth in consideration of money or money's worth, or
    b. the making of a payment in respect of any toll or duty.

3. Use for trade does not include use in a case where—
    a. the determination or statement is a determination or statement of the quantity of goods required for despatch to a destination outside Great Britain and any designated country, and
    b. the transaction is not a sale by retail, and
    c. no transfer or rendering of money or money's worth is involved other than the passing of the title to the goods and the consideration for them.

4. The following equipment, that is to say—
    a. any weighing or measuring equipment which is made available in Great Britain for use by the public, whether on payment or otherwise, and
    b. any equipment which is used in Great Britain for the grading by reference to their weight, for the purposes of trading transactions by reference to that grading, of hens' eggs in shell which are intended for human consumption, shall be treated for the purposes of this Part of this Act as weighing or measuring equipment in use for trade, whether or not it would apart from this subsection be so treated.

Where any weighing or measuring equipment is found in the possession of any person carrying on trade or on any premises which are used for trade, that person or, as the case may be, the occupier of those premises shall be deemed for the purposes of this Act, unless the contrary is proved, to have that equipment in his possession for use for trade

There is currently no national legislation for the accuracy of metering hydrogen as a gas for fueling motor vehicles, in the UK, therefore it would be necessary to contact any (commercial) users to establish the methods – if any – related to metering accuracy including the processes and reference equipment used involved and the traceability of the measurements.
The HONDA Motor Company vehicle assembly plant, situated in Swindon (UK), have a fuel station which is used for re-fueling the forklift trucks operating within the plant. The station is not generally available to the general public.

London transport now has a fleet of eight hydrogen fuel buses running on route RV1 between Covent Garden and Tower Gateway.

1.2.2 Scandinavia

The Scandinavian countries Norway, Sweden and Denmark have various regulation basis for fuel metering as outlined below:

- Sweden
  SWEDAC is the Swedish authority for regulation of fuel metering accuracy. Meter accuracy for fuel meters distributing fuel in the state of gas, is not covered by any regulations in Sweden today. Fuels that are in the state of gas when they are filled in a fuel station are not covered by the MID directive. The OIML's recommendations R 139 are probably used by the manufacturers of the metering equipment on a voluntary basis.
- Norway
  Justervesenet (JV) is the Norwegian authority for regulation of fuel metering accuracy. Meter accuracy for fuel meters distributing fuel in the state of gas is not covered by any regulations in Norway today. Decisions taken by the Ministry of Trade and Industry during 2011 were not to include legislation for gas metering accuracy.
- Denmark
  The Danish Safety Technology Authority is handling regulation of fuel metering accuracy. The MID-directive Annex MI-002 "Gas meters and volume conversion devices" applies in Denmark and this also includes gas meters for the automotive sector in Denmark. OIML R 139 "Compressed gaseous fuel measuring systems for vehicles" is also to be applied.

The main experience on hydrogen metering accuracy in Scandinavia is mainly based on Hydrogen Refuelling Stations (HRS) installed and operated in Denmark.

The MID directive OIML are not used as basis for hydrogen metering in Denmark (as hydrogen is not included).

Since 2008 more than 10 fueling stations of various pressures have been demonstrated in Denmark. This has created basis for developing a pragmatic approach to handling hydrogen metering, despite no regulation or standard is in place.

The Danish Safety Technology Authority is handling metering accuracy in Denmark. Based on a dialogue a methodology has been developed that includes a third party validation of the hydrogen metering accuracy prior to installation of a HRS.

The validation is based on weighing the amount of hydrogen fuelled into a test tank, using precision scales. The tests are done prior to start of HRS operation and is monitored by a third party that calculates the accuracy (% deviation) and issues a test report. In general a consistent accuracy of a few % deviation have been observed on the HRSs installed.

The approach does not necessarily ensure a coherent approach to accuracy measurement but it ensure that attention is put on accuracy before installing an HRS.

When hydrogen at a later stage is included in European directives and/or standards, it is likely that this will be implemented in Denmark.

1.2.3 Germany

In Germany activities on hydrogen accuracy is in particular conducted under the public-private the Clean Energy Partnership (CEP). CEP is a joint initiative of government and industry lead-managed by the German Ministry of Transport and Industry with twenty industry partners.

Within the CEP a dedicated working group is active on various hydrogen metering topics:

- Assess fueling data and matching hereof between cars and fueling station
- Asses status on development and availability of metering devices
- Test the accuracy of current metering methods and asses technical feasibility
- Explore variants of Measuring Mass(transfer)

The aim is to establish a metering method in coordination with German authorities (Eichamt) and agencies (e.g. PTB - the National Metrology Institute of Germany).

In 2013 the CEP initiative published results from accuracy tests conducted at various HRSs in Germany. On average 35 % of all refuelings had a deviation above 9% and generally the higher the refueled quantities the lower the deviation. Presently the “Weights and Measures Act” applicable for CNG only allows +- 2% deviation.

CEP are at present executing a 3-step-development-program to further address the accuracy topic. This includes a feasibility study on measurement methods, development of prototype measurement equipment for laboratory and later for in-field testing.

CEP has also formulated some initiation boundary conditions for hydrogen accuracy (2013):

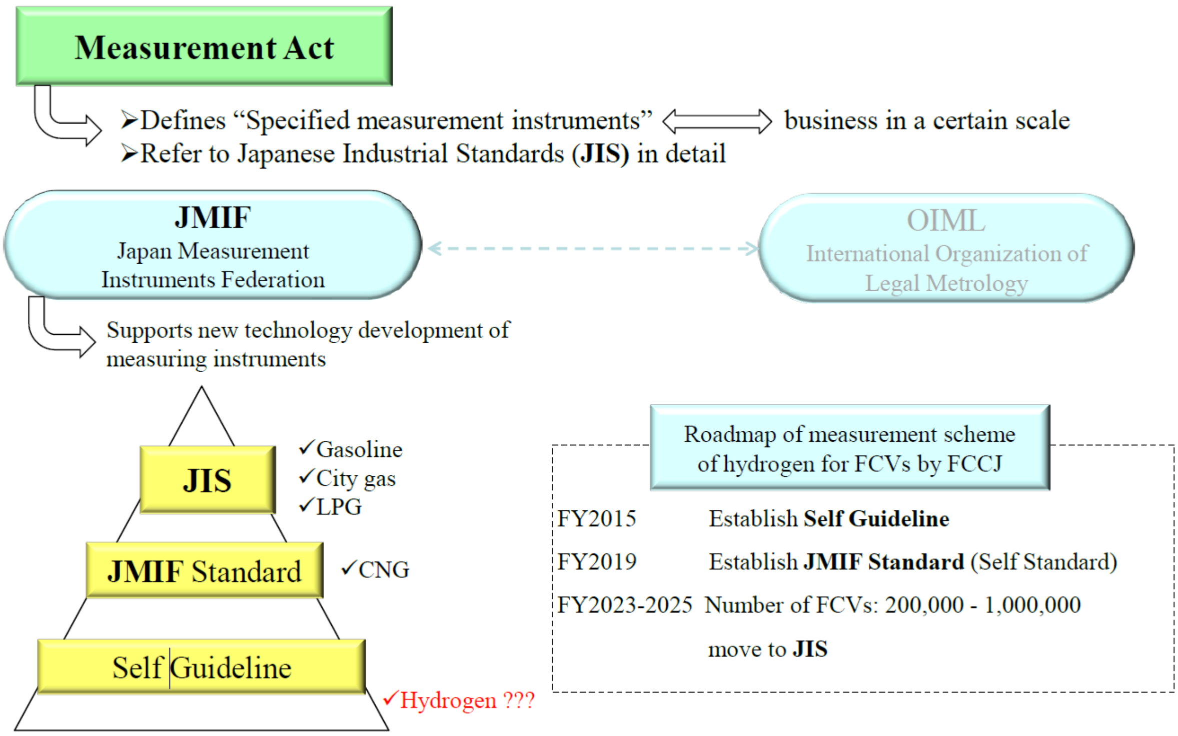
- Medium: CGH2
- Pressure: up to 87.5 MPa
- Temperature window : +50°C -40°C , high gradient (cool down from ambient temperature to -30°C in <30 seconds)
- Max. mass flow: 50 g/s, operating range between 33 - 34 g/s
- Min. mass flow: < 5g/s
- Pipe diameter: 3/8"
- Average refueling amount: 2-4 kg, a minimum amount has not yet been defined

1.2.4 Japan

At present there is no governmental regulations on hydrogen metering so instead suppliers are only to measure as accurate as possible.

In Japan NEDO is therefore facilitating a project with the aim to establish technical standards for Gravimetric and Master Meter Methods on hydrogen accuracy and metering.

The existing Measurement Act structure in Japan and the possible integration of hydrogen is outlined in the figure below.

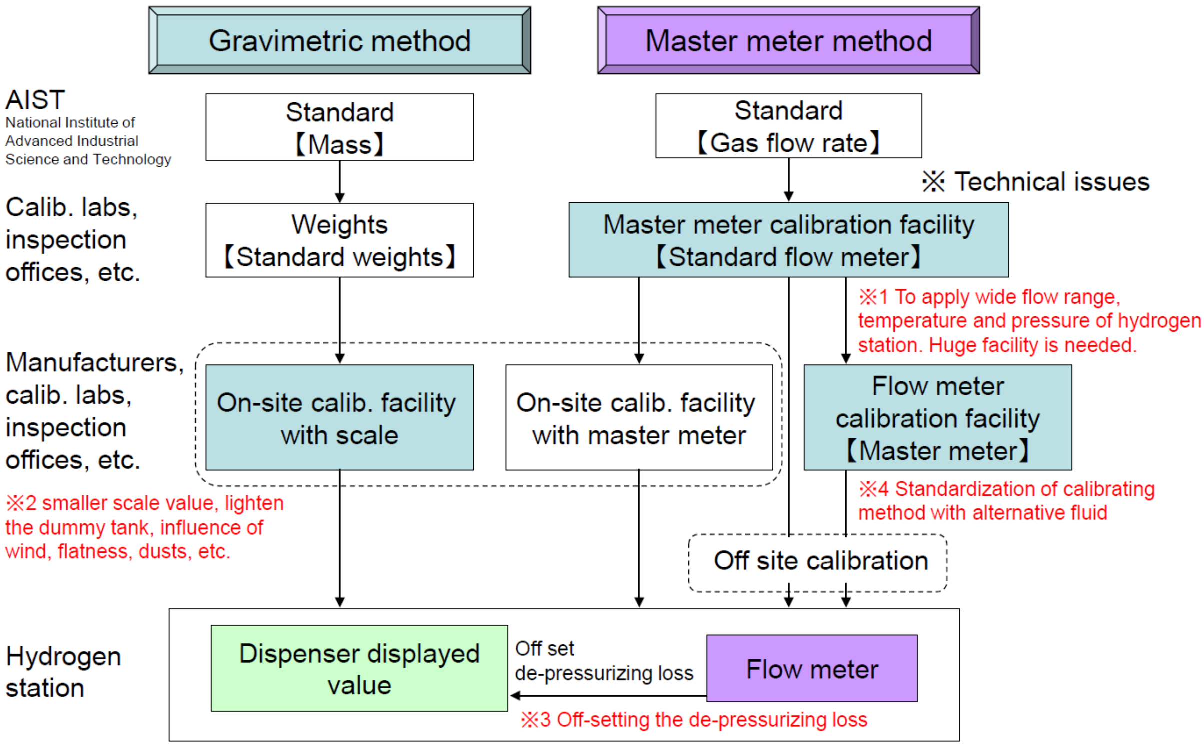


The aim of the NEDO project is to firstly establish a voluntary Self Guideline based on "Gravimetric method" before 2015. This can then be used for manufacturers own assessment of accuracy.

After collecting sufficient technical data and results from use of the voluntary guideline it is to be updated with a "Self Standard" based on "Master Meter method" scheduled onwards 2019.

The technical approach in Japan is firstly to use the Gravimetric method as this is technically feasible and achievable today. As the data and experience basis mass flow meters are increase this may enable a new and more simple approach using a calibrated master flow meter as measurement basis.

The approach is outlined in the figure below.



1.2.5 USA/California

The experience in USA on hydrogen metering is in particular linked to the HRS roll-out efforts in California.

In order to offer commercial sale of hydrogen, A HRS operate must receive a Certificate of Approval that indicates the dispenser accurately measures the amount of hydrogen it dispenses during sales to customers.

California's Department of Food and Agriculture (CDFA) is the authoritative agency for motor fuel sales certification and also hydrogen. CDFA has adopted the standards outlined in the National Institute of Standards and Technology Handbook 44 (NIST 44).

The NIST 44 outlines weighing and measuring devices of which the section 3.39 is relevant for hydrogen dispensing and specifies a tolerance of 1.5% for acceptance (typically for commissioning) and 2% for maintenance (or continued operation).

The table below outlines the NIST 44 accuracy targets:

Accuracy Class	Commodity	Acceptance Tolerance	Maintenance Tolerance
2.0	Hydrogen as a Vehicle fuel	1.5%	2.0%

To support adoption of the standard several organizations have collaborated on designing, building and testing a "Hydrogen Field Standard (HFS) Metrology Testing Device". It was built to follow the requirements of NIST 44 and has tested most of the currently-operating HRS.

Based on the results and analyses completed, CDFA is the process of adopting regulation to establish three additional accuracy classes of 3%, 5%, and 10%, based on certification with the HFS device. The relaxed targets are outlined in the table below.

Accuracy Class	Acceptance Tolerance	Maintenance Tolerance	For Dispensers Installed Prior To
2.0	1.5%	2.0%	N/A
3.0	2.0%	3.0%	1/1/2020
5.0	4.0%	5.0%	1/1/2020
10.0	5.0%	10.0%	1/1/2018

HRS's will be able to receive certification to one of these degrees of accuracy. Distinction will be made between accuracy of HRS at commission and testing conducted as part of normal operation. The intent is to relax today for the present HRS technology, and then to increase the targets as the technology progresses.

2. Boundary conditions for hydrogen mass flow meters

The project has developed a proposal for boundary conditions for mass flow meters used for 70MPa hydrogen.

The aim is to provide mass flow meter suppliers with a better understanding of the operation environment in which the component is to be used at 70MPa Hydrogen Refueling Stations (HRS).
The boundary conditions stem from the SAE J2601 refueling protocol with specifies a very precise definition of 70MPa hydrogen refueling.

Based on this the suppliers can describe the specific issues that may be for mass flow meters in coping with the conditions and operation environment. This can lead to suggestions for a definition of hydrogen metering accuracy that takes into account those issues.

2.1 HRS Refueling principle & location of mass flow meter

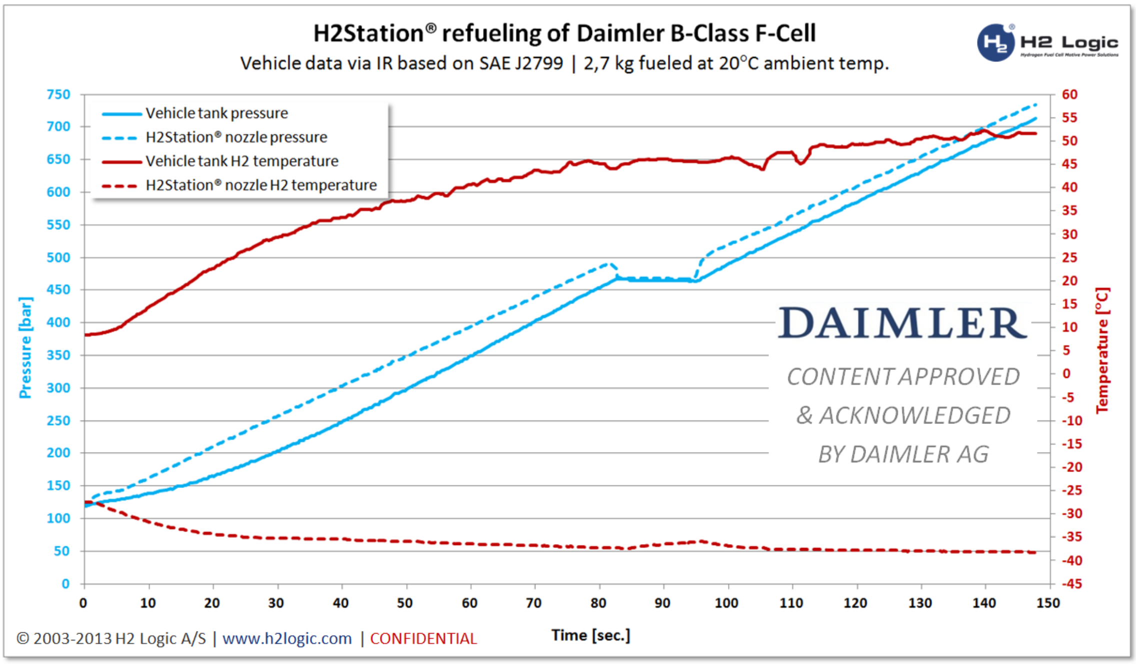
State-of-the-art 70MPa refueling is conducted using a cascade principle, possible in combination with a compressor. In order to full-fill the SAE J2601 standard hydrogen is pre-cooled during the refueling down to minus 40 degrees Celsius.

The SAE J2601 standard defines how a 70MPa refueling is to be conducted in order to be safe, uniform and fast. With regards to mass flow meters the standard provides a very specific definition of the various “refueling situations” that can occur (various temperature, pressures, flows etc.).

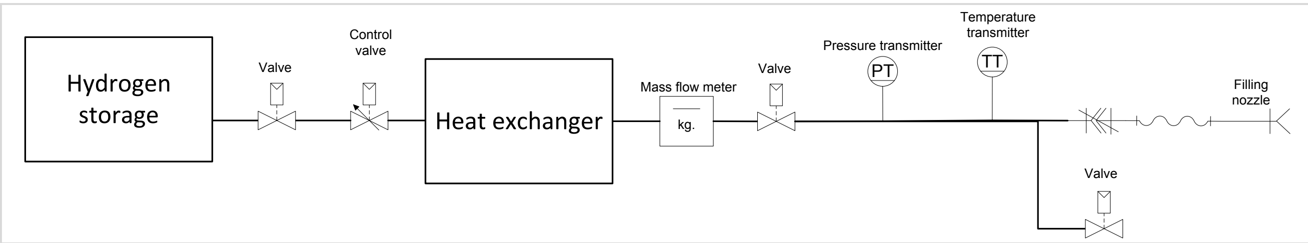
The SAE standard defines the method and values to be used in any given refueling, depending on the boundary conditions of that refueling. A table look-up (from the SAE J2601 standard) is made of the Average Pressure Ramp Rate (APRR) depending on the type of fueling (communication or non-communication), the ambient temperature, the pressure of the vehicle and the status of the station.

This APRR is a definition of how much the pressure should increase per second. This pressure increase should be followed during the entire filling, with limited error margin. The vehicle tank sizes are split into three ranges (2-4 kg, 4-7 kg and 7-10 kg). The refueling within a tank range happens with the same APRR, which means that the mass flow varies depending on the size of the vehicle tank.

Below is shown an actual SAE J2601 refueling of a Mercedes B-Class F-Cell FCEV.



The exact location of the mass flow meter in the HRS design and system may vary depending on manufacturer. The figure below shows a simplified P&ID diagram of how the mass flow meter could be located in a HRS. In this example the mass flow meter is situated after the station, the control valve and the heat exchanger; close to the filling nozzle. This is to avoid having a large pipeline after the flow meter which needs to be filled with hydrogen, resulting in a wrong flow measurement compared to what is delivered to the vehicle.

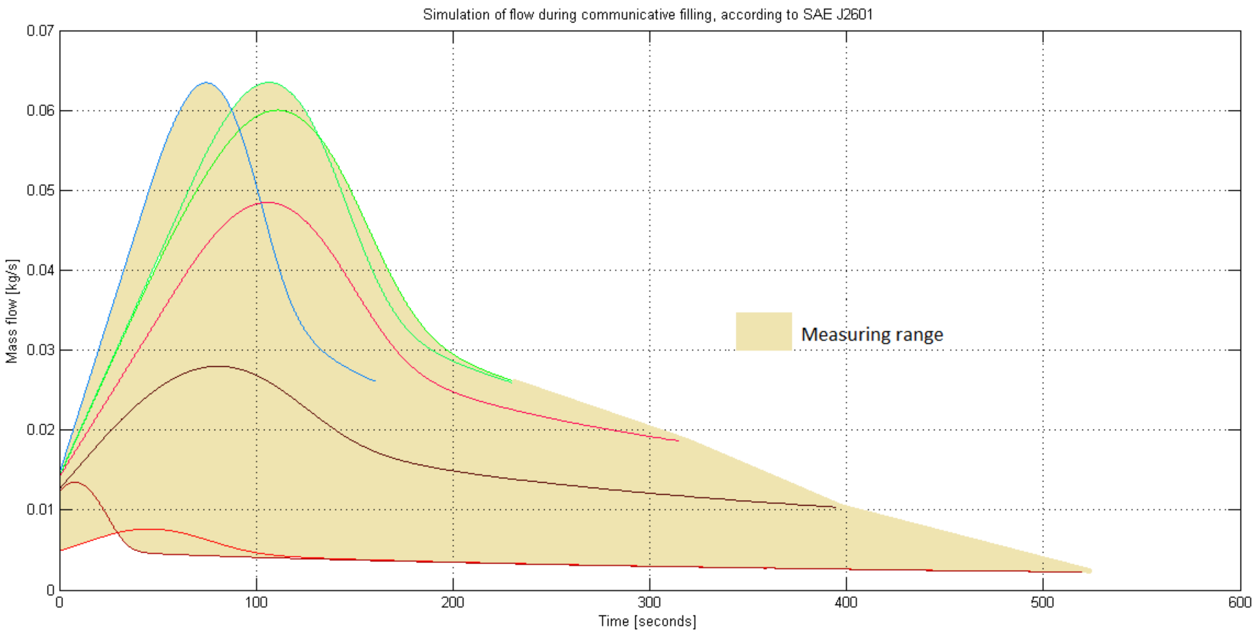


Example of a simplified P&ID diagram in relation to a mass flow meter

2.2 Flow curve spectrum

The minimum and maximum mass flow, the flow meter should be able to measure, can be seen on the figures in the sections below.

2.2.1 Simulation of mass flow range as a function of time



The graph above shows maximum and minimum mass flow for refueling with a variant elapse.
The graph is made based on simulations of maximum and minimum flow when refueling according to the SAE J2601 and -40 degrees Celsius pre-cooling. Note that there are peak flows which are higher than 0.06 kg/s. This is because of precision of the simulation model.

The flow during fuelling can move anywhere within the measuring range at a given time (depending on starting conditions for the fueling). For instant after 100 sec. the mass flow is between 0.06 g/s and 0.004 g/s if the flow is not stopped and equal to zero. When there is a flow this simulation shows that the flow varies between 0.06 g/s and 0.002 g/s. The filing takes different time depending on the size and state of charge of the tank.

The flow range during a refueling however follows some simplified principles:

- The smaller tank and/or higher ambient temperature the lower flow
- The larger tank and/or lower ambient temperature the higher flow
- Vehicle tank State-of-Charge at start of refueling (may) only affect flow very little
- The higher pre-cooling temperature the lower flow
- The lower pre-cooling temperature the higher flow
- The higher pressure drop (nozzle-vehicle tank) the lower flow
- The lower pressure drop (nozzle-vehicle tank) the higher flow

2.2.2 Simulation of mass flow range as a function of nozzle pressure

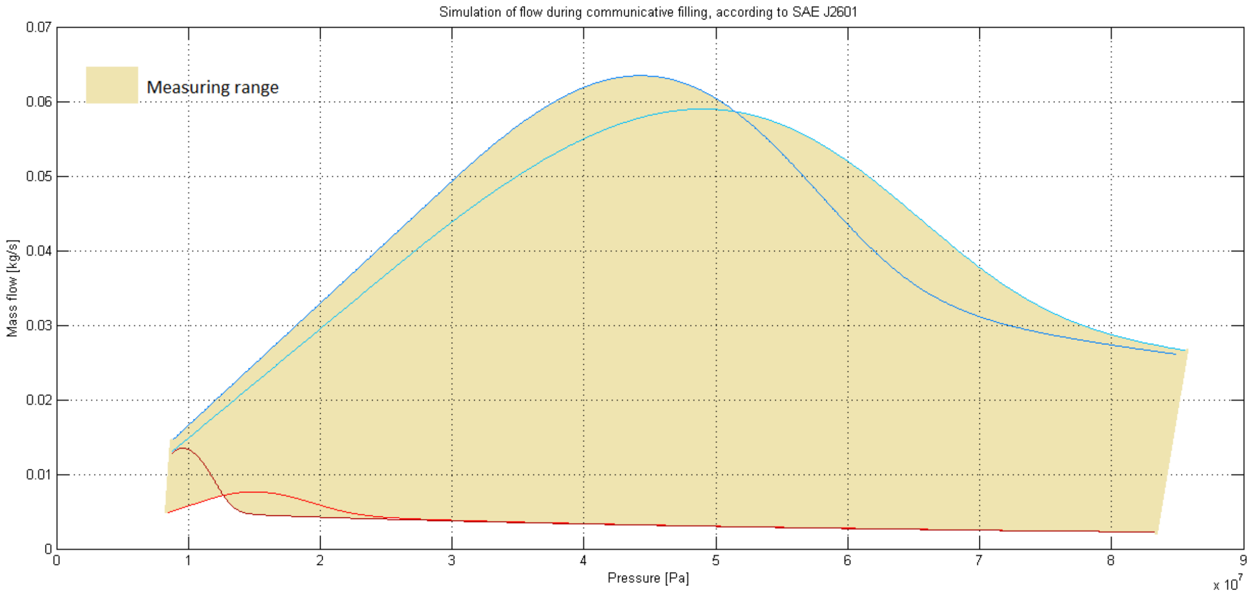
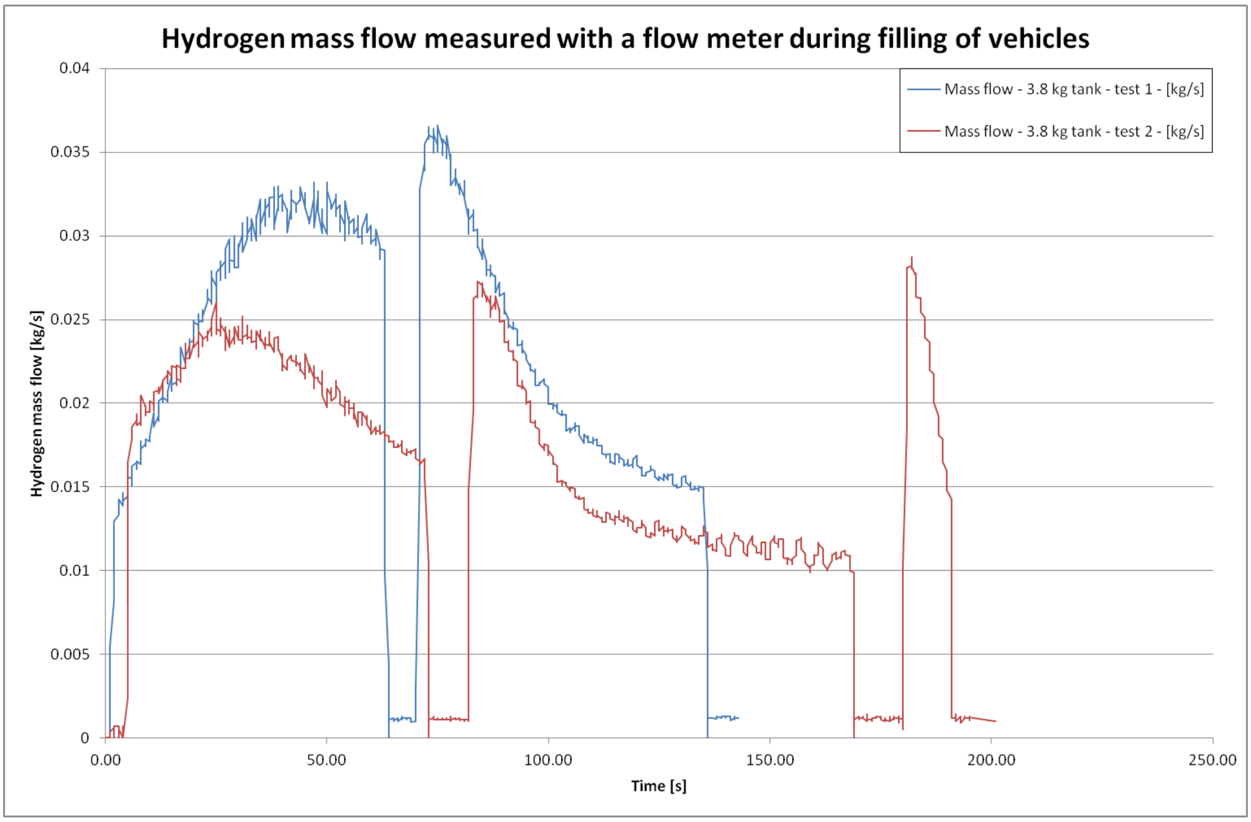


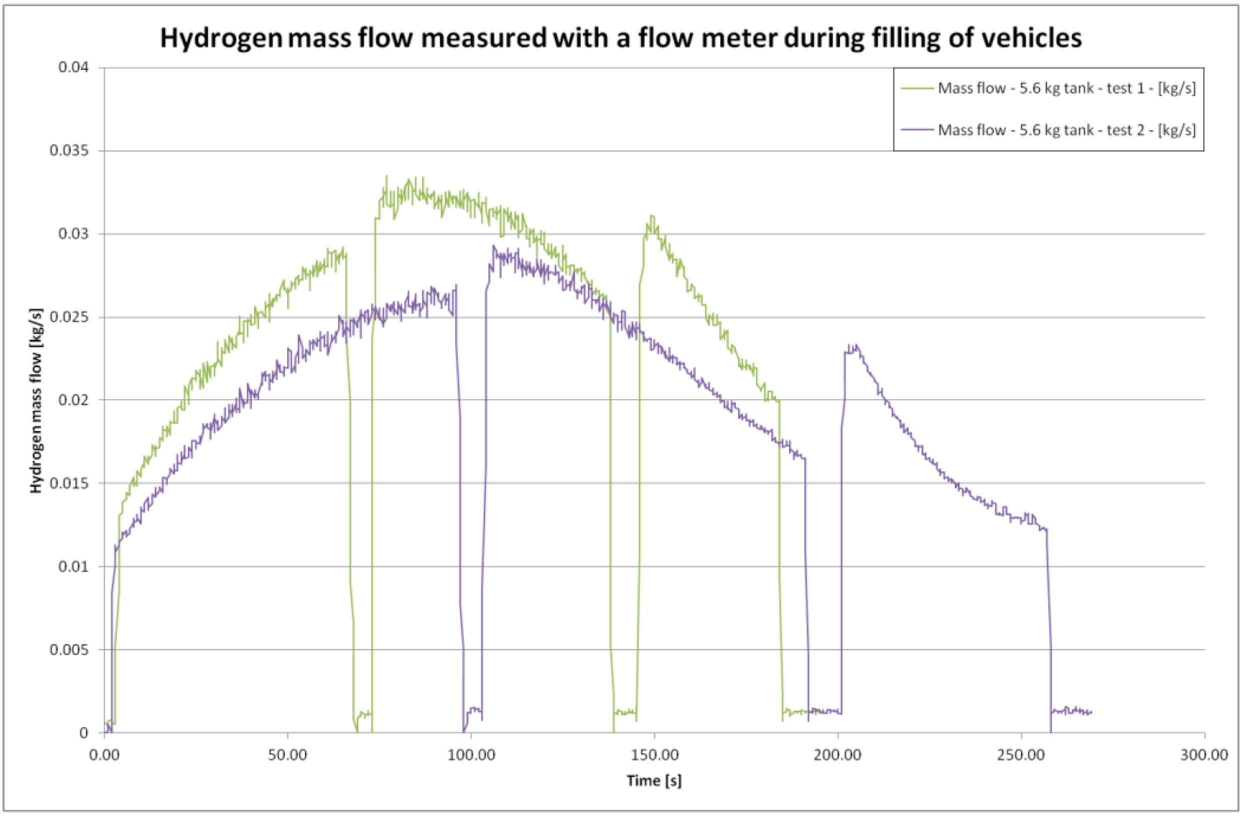
Figure above shows the mass flow as a function of the nozzle pressure during the filling. It should be noted that the pressure starts at 8.5 MPa. This is because the figure shows the pressure of the refueling nozzle and not the vehicle pressure.

The maximum mass flow of 0.06 g/s is reached at a pressure of approximately 40 – 50 MPa. However note that the mass flow can peak at any other pressures. The max flow varies with the pressure drop over the nozzle to the vehicle. The curve can have any shape within the shown measuring range.

2.2.3 Examples of mass flow measured during an actual refueling

Graphs below show two test refueling's of respectively a 3.8 and 5.6 kg vehicle tank.





As can be seen the mass flow during the two refueling did not come close to the maximum and minimum flow (as simulated earlier). However it should be kept in mind that each filling can be very different from one another, depending on the boundary conditions.

These figures show that there are stops and starts of the filling which is because the hydrogen storage bank at the station is changed to one with a higher pressure (cascade).

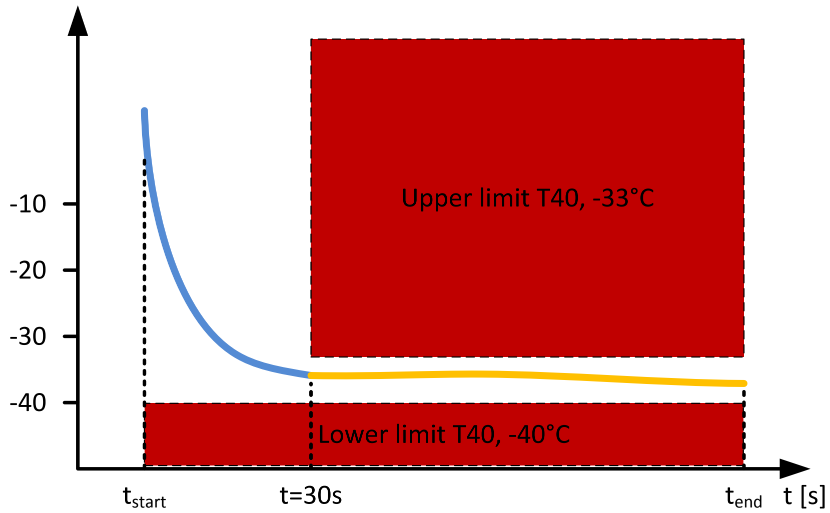
It should also be noted that the filling can take more than 500 seconds and there could be more short stops than seen on the above graphs.

The pressure pulses (prior to start of refueling ramp) are not shown on the graphs – these has a pressure up to 70 MPa and lasts a couple of seconds. These pressure pulses can result in a change of pressure from 0.5 MPa to 70 MPa within a second. The mass of this pulse can be up to 0.2 kg, but the flow is below the maximum mass flow of 0.06 kg/s as stated above. The flow meter should also be able to measure the mass flow during this pulse.

2.3 Media and ambient conditions

Below are listed media and ambient conditions for 70MPa refueling:

- Media: hydrogen
- Temperature: -40 to 50 °C
- Pressure: 0.5 – 96.3 MPa
- Density: 0.37 – 53 kg/m3
- Flow rate: 0-0.06 kg/s
- Absolute flow: 2 to 10 kg per filling
- Absolute flow: 0 to 2 kg per filling in case of a user interruption or emergency stop
- Pressure drop <1 MPa @ maximum flow rate
- Hydrogen temperature corridor as seen below as a function of time



- Ambient temperature: -40 to 50 °C
- Ambient pressure: Normal ambient pressure

2.4 Other conditions

2.4.1 Approval

The flow meter should be approved according to

- PED
- EMC
- ATEX zone 2 IIC (only a requirement for the sensor part if the controller can be moved more than 10 meters from the sensor) and be
- CE approved and documented.
- Documentation that all wetted material can be used for hydrogen (withstanding e.g. hydrogen embrittlement)

2.4.2 Connections

- 1 Analogue output 4-20mA
- At least 1 digital output, preferably 2 digital output pulses 90° phase between the pulses; 2 pulses are required for payment systems. The frequency of the pulses should be between 0.6 – 1 kHz.
- Process connection: Standard Auto clave medium pressure fittings 3/8’’ (or 9/16’’)

2.4.3 Other conditions:

Temperature of the flow meter can change from ambient to -40 °C within 30 sec., but the flow meter can also be constantly at -40 °C when having consecutive refuellings.

It should be able to measure flow in the whole range and at the same time have a reasonable resolution.

It is a highly dynamic mass flow, going from no flow to full flow within a second and from full flow to zero flow within a second. This happens during the pressure pulses, or during start/stops of the filling. This requires a fast response and settle-time. The response time is not as such defined, but it has an impact on the error of the measurement.

The flow meter should still be working when having short stops, going to zero flow for limited time and starting again – this is important to take into consideration when looking at the precision of the flow meter. For instant if it is not having a signal of zero when there is no flow it will have an influence the precision of the flow meter. The flow meter measurement is not started before the filling actually starts, so any ghost flow before the filling is not relevant.

As the flow meter should be sitting in a small compartment and have as little thermal mass, size does matter. It is expected to be less than 2-3 liter.

3. Mass flow meter optimization & accuracy test equipment

3.1 Accuracy optimized hydrogen mass flow meter

As part of the project existing hydrogen mass flow meter technology has been optimized with regards to accuracy.

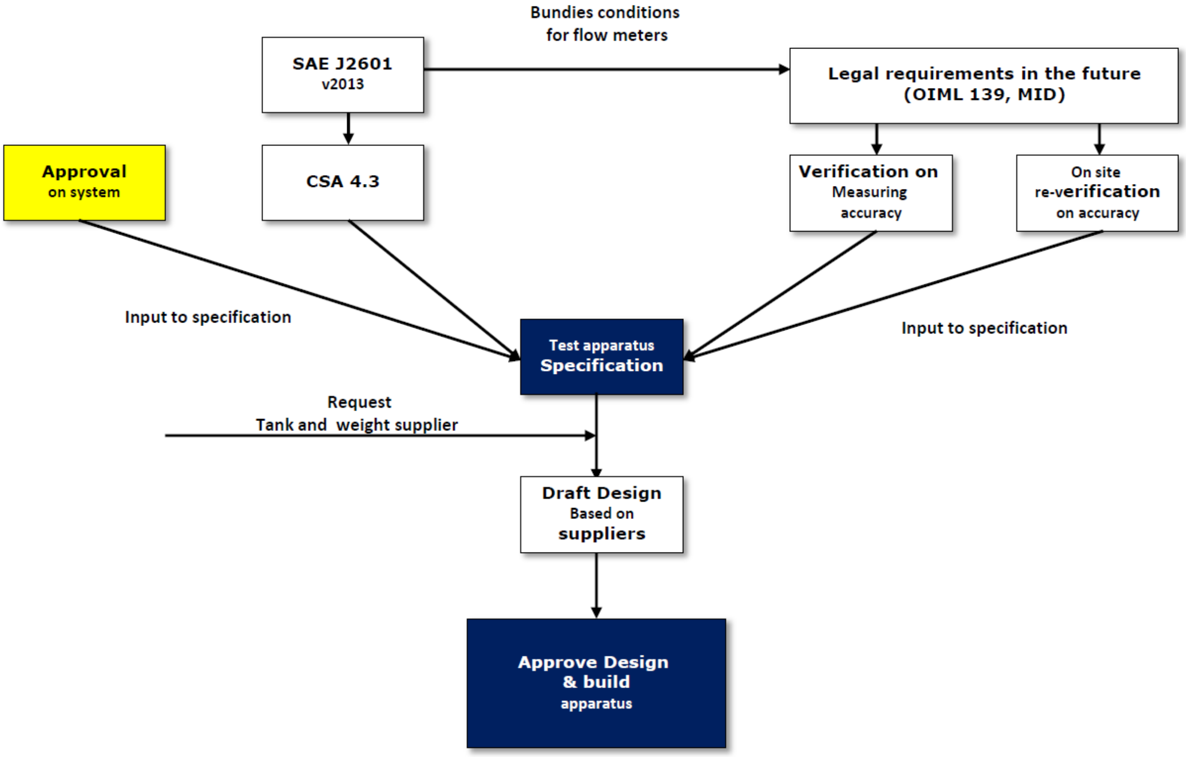
This has been done by conducting development of improved meter designs where a range of parameters are changed and tested to asses the impact on flow and accuracy.

Below are listed the main design parameters.

1. **Reducing wall thickness**
   Higher sensitivity by reducing the wall thickness of the measuring pipes and using smaller inner pipe diameters. Tests are to define the maximum possible flow velocity in the meter, defining the minimum H2 pressure and reaching the target accuracy.
2. **Increasing measuring frequency – reduced wall thickness**
   Higher sensitivity by reducing the wall thickness, using smaller inner pipe diameters and by increasing the measuring frequency. Tests are to define the maximum possible flow velocity in the meter, defining the minimum H2 pressure and reaching the target accuracy.
3. **Larger inner pipe diameter**
   Higher sensitivity by reducing the wall thickness and using a larger inner pipe diameters. Tests are to define the minimum possible flow velocity in the meter, defining the minimum H2 pressure and reaching the target accuracy.
4. **Increasing measuring frequency – larger inner pipe diameter**
   Modifications: Higher sensitivity by reducing the wall thickness using bigger inner pipe diameters and by increasing the measuring frequency. Purpose of tests with this meter: defining the minimum possible flow velocity in the meter, defining the minimum H2 pressure and reaching the target accuracy.

3.2 Formulation of test procedures and specifications

A range of detailed test procedures and specification has been compiled based input and inspiration from a range of sources as outlined in the figure below.



The input sources combines relevant hydrogen specific knowledge generated inside the project and outside, e.g. SAE J2601 and CSA 4.3. In addition the existing legal requirements and methodologies for gas metering used in OIML and MID is also taken into account.

This has resulted in the formulation of a general test specification and specific test procedures and steps. This also acts as basis for the test equipment to be developed.

3.2.1 Test specification

Below are listed the detailed specification of requirements for test procedures as developed.

Test procedures and specifications	Requirements
Constant flow rates: Tests at constant flow rates have to be implemented for demonstrating the intrinsic performances of the meter for a complete application of this Recommendation. However, for national applications they may be replaced by alternative suitable testing conditions. In this case the national Authority should consider additional different testing conditions providing a sufficient variety of supplying conditions in addition to those already foreseen for the measuring system.	3x FR 1: Min value: *Qmin* Max value: (*Qmax* + 4×*Qmin*)/5 3x FR 2: Min value: (*Qmax* + 4×*Qmin*)/5 Max value: (2×*Qmax* +3×*Qmin*)/5 3x FR 3: Min value: (2×*Qmax* +3×*Qmin*)/5 Max value: (3×*Qmax*+2×*Qmin*)/5 3x FR 4: Min value: (3×*Qmax*+2×*Qmin*)/5 Max value: (4×*Qmax* + *Qmin*)/5
Accuracy test (1): Measuring systems (MS) tested with three banks may be used in all situations, whatev-	3x Test 1: Initial test receiver pressure of 0 bar Initial station storage pressure of *Pst* in all banks

er the number of banks (1, 2, 3, 4…) may be. Switching time from one bank to another as fast as possible, but in max. 3 s. • Cascade filling	3x Test 2: Initial test receiver pressure of 0.5×*P*v Initial station storage pressure: - high bank at *P*st, - medium bank at close to *P*v, - low bank at 0.75×*P*v. 3x Test 3: Initial test receiver pressure of 0.75×*P*v Initial station storage pressure: - high bank at *P*st, - medium bank at close to *P*v, - low bank at 0.75×*P*v.
Accuracy test (2): Measuring systems (MS) tested with only one bank. • No switching • No cascade filling	3x Test 7: - minimum measured quantity - For this purpose, the pressure does not have to be *P*v in the test receiver at the end, but may be any pressure (as close as practical to *P*v) such that the quantity of transferred gas shall be at least the minimum measured quantity.
Tolerance on gas pressure:	(The tolerance to be applied to all test pressures (0.5×*P*v, 0.75×*P*v, *P*v and *P*st) is ±10 bar.

*P*st – Maximum pressure of the gas in the refueling station gas storage (95 MPa)

*P*v – Maximum fast fill pressure of the gas-fueled vehicle (70 MPa)

(In the following pressure values are given for standard conditions, 15°C etc.)

3.2.2 Accuracy testing steps:

Below are listed the developed proposal for accuracy testing steps and procedures.

1. Setting up a large weighing scale (350 kg)

2. Setting up the dispenser with the complete measuring unit (flow meter, heat exchanger, piping, valves, hose, nozzle) next to the weighing scale.

3. Place the tank (resp. tank system) on the weighing scale.

4. Test 1: "Empty tank"
    a. Empty the tank system as close to 0 MPa as possible.
    b. Weigh the empty system, set the weighing scale to zero.
    c. Bank pressure must be maximal in all banks (95 MPa).
    d. Connect the nozzle to the system.
    e. Refuel the system till maximum pressure (70 MPa).
    f. Disconnect the nozzle from the system.
    g. Weigh the amount of hydrogen in the tank.
    h. Report the value measured by the flow meter.

5. Test 2: "Half full tank"
    a. Empty the tank system as close to 35 MPa as possible.
    b. Weigh the system, set the weighing scale to zero.
    c. Bank pressure must be:
        i. Maximum in high bank (95 MPa)
        ii. Medium bank at 70MPa
        iii. Low bank at 52,5 MPa
    d. Connect the nozzle to the system.
    e. Refuel the system till maximum pressure (70 MPa). Start refueling from low, medium and at last high bank.
    f. Disconnect the nozzle from the system.
    g. Weigh the refueled amount of hydrogen in the tank.
    h. Report the value measured by the flow meter.

6. Test 3: "Three quarter full tank"
    a. Empty the tank system as close to 52,5 MPa as possible.
    b. Weigh the system, set the weighing scale to zero.
    c. Bank pressure must be:
        i. Maximum in high bank (95 MPa)
        ii. Medium bank at 70MPa
        iii. Low bank at 52,5 MPa
    d. Connect the nozzle to the system.
    e. Refuel the system until the maximum pressure (70 MPa).
    f. Disconnect the nozzle from the system.
    g. Weigh the refueled amount of hydrogen in the tank.

   h. Report the value measured by the flow meter.

7. Test 4: "Minimum measured quantity"
   a. Empty the tank system close to 0 MPa.
   b. Weigh the empty system, set the weighing scale to zero.
   c. No requirements for initial bank pressure (find out through prior testing; at least one bank has to be on full pressure)
   d. Connect the nozzle to the system.
   e. Refuel the system with the minimal flow rate (make sure that this flow rate still stays constant near to Pv).
   f. Refuel the system as close as practical to 70 MPa. Make sure that the transferred gas is at least the minimum measured quantity.
   g. Disconnect the nozzle from the system.
   h. Weigh the amount of hydrogen in the tank.
   i. Report the value measured by the flow meter.

8. Repeat all four tests (1,2,3,4) three times each (maybe another order makes more sense wrt hydrogen savings)

9. Minimal required amount of pressurized (refueling) hydrogen if testing with a 7kg tank system:
   a. Test 1: 0 to 7 kg → 7 kg
   b. Test 2: ~4 to 7 kg → 3 kg
   c. Test 3: ~5,7 to 7 kg → 1,3 kg
   d. Test 4: 0 to ~7 kg → 7 kg
   e. <u>Total: 3x 18,3 kg = 54,9 kg</u>

3.3 Mass flow meter accuracy test equipment

As part of the project a prototype metering accuracy test system has been developed and constructed.

The system includes a range of storage vessels of different volumes – representing different vehicle tank sizes. The vessels can be used in combination to simulate vehicles with multiple tanks or individually to both represent different tank sizes and different types of fuelings.

The system has its own control system to handle the different fueling tests and set-ups. Mass flow meters are installed manually for every tests in order to enable test of products from various suppliers.

4. Hydrogen accuracy fueling tests

A range of 70MPa fueling tests has been conducted within the project, with the aim to test the developed test equipment with regards to measuring and validating accuracy of the mass flow meter.

A total of 16 fueling tests and accuracy measurements were conducted, allocated on 4 sessions, of which 2 was supervised and acknowledged by a legally accredited third party.

The accuracy test method uses a very precise weighing device to measure the weight of the tank vessel before and after a fueling, thus providing an exact measurement of the fueled hydrogen mass. This measurement is then compared to the mass flow meter reading from the fueling and based on this the accuracy is calculated.

Accuracy is the deviation in % between the measured hydrogen mass and the mass flow meter. A negative deviation means that more hydrogen was fueled than actually measured by the mass flow meter, and opposite for a positive deviation.

The tests shows that the present equipment and methodology today provides a reasonable accuracy. Measured accuracy deviation ranges from -5,352% to +0,65%. On average the measured deviation was negative, meaning a fueling customer would gain more hydrogen that actually charged for by the mass flow meter reading.

The detailed test results from the 16 fuelings and measurements are shown in tables below, for each of the 4 sessions.

4.1 Hydrogen mass flow meter accuracy test – session 1

Hydrogen mass flow meter accuracy test - session 1

No.	m_e (Test vessel empty)	m_f (Test vessel full)	dm = m_f - m_e (Weighed hydrogen amount)	m_f1 Flow meter	dm - m_f1 deviation	**Deviation**	Precision incl. Weighing scale +2 g	Precision incl. Weighing scale -2 g
	[kg]	[kg]	[g]	[g]	[g]	**[%]**	[%]	[%]
1	56,3130	57,6290	1316,0	1318,0000	2,0000	**0,152**	0,303	0,000
2	56,3615	57,6615	1300,0	1303,0000	3,0000	**0,231**	0,384	0,077
3	56,4610	56,9935	532,5	504,0000	-28,5000	**-5,352**	-4,958	-5,749
4	56,9935	57,6240	630,5	632,0000	1,5000	**0,238**	0,553	-0,080
5	56,7015	57,3300	628,5	605,0000	-23,5000	**-3,739**	-3,410	-4,070

4.2 Hydrogen mass flow meter accuracy test – session 2

Hydrogen mass flow meter accuracy test - session 2

No.	m_e (Test vessel empty)	m_f (Test vessel full)	dm = m_f - m_e (Weighed hydrogen amount)	m_f1 Flow meter	dm - m_f1 deviation	**Deviation**	Precision incl. Weighing scale +2 g	Precision incl. Weighing scale -2 g
	[kg]	[kg]	[g]	[g]	[g]	**[%]**	[%]	[%]
1	56,1370	57,5935	1456,5	1440,0000	-16,5000	**-1,133**	-0,994	-1,272
2	56,2160	56,9140	698,0	680,0000	-18,0000	**-2,579**	-2,286	-2,874
3	56,3560	57,6530	1297,0	1290,0000	-7,0000	**-0,540**	-0,385	-0,695

4.3 Hydrogen mass flow meter accuracy test – session 3

Hydrogen mass flow meter accuracy test - session 3

No.	m_e (Test vessel empty)	m_f (Test vessel full)	dm = m_f - m_e (Weighed hydrogen amount)	m_f1 Flow meter	dm - m_f1 deviation	**Deviation**	Precision incl. Weighing scale +2 g	Precision incl. Weighing scale -2 g
	[kg]	[kg]	[g]	[g]	[g]	**[%]**	[%]	[%]
1	56,0780	57,3980	1320,0	1302,0000	-18,0000	**-1,364**	-1,210	-1,517
2	56,3430	57,3715	1028,5	1001,0000	-27,5000	**-2,674**	-2,475	-2,874
3	56,3525	57,3780	1025,5	1002,0000	-23,5000	**-2,292**	-2,092	-2,491
4	56,3685	57,3620	993,5	1000,0000	6,5000	**0,654**	0,854	0,454
5	56,3715	57,3910	1019,5	1002,0000	-17,5000	**-1,717**	-1,517	-1,916

4.4 Hydrogen mass flow meter accuracy test – session 4

Hydrogen mass flow meter accuracy test - session 4

No.	m_e (Test vessel empty)	m_f (Test vessel full)	dm = m_f - m_e (Weighed hydrogen amount)	m_f1 Flow meter	dm - m_f1 deviation	**Deviation**	Precision incl. Weighing scale +2 g	Precision incl. Weighing scale -2 g
	[kg]	[kg]	[g]	[g]	[g]	**[%]**	[%]	[%]
1	56,0940	57,5970	1503,0	1490,0000	-13,0000	**-0,865**	-0,731	-0,999
2	56,4230	57,1470	724,0	700,0000	-24,0000	**-3,315**	-3,030	-3,601
3	56,3875	57,4075	1020,0	1000,0000	-20,0000	**-1,961**	-1,761	-2,161