JRC REFERENCE DATA FROM EXPERIMENTS OF ONBOARD HYDROGEN TANKS FAST FILLING

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ABSTRACT

At the JRC-IET, commercial hydrogen tanks have been subjected to filling-emptying cycles to investigate their long-term mechanical and thermal behaviour and their safety performance. The local temperature history inside the tanks has been measured and compared with the temperatures outside and at the tank metallic bosses, which is the measurement location identified by some standards. The outcome of these activities is a set of experimental data which will be made publicly available as reference for safety studies and CFD validation. Comparison with the available RCS is also presented in this paper.

1. INTRODUCTION

Hydrogen technologies, as well as all other new energy technologies, have to comply with a set of safety standards and regulations. Common sense approach is that the new technology has to guarantee the same as or better safety level than the already widely adopted technologies. Due to the specific and unique aspects of the hydrogen technologies, in the past years standardisation and regulatory bodies have been intensely busy in adapting existing, and in many cases developing completely new regulations, codes and standards (RCS) concerning the performance assessment and safety testing of hydrogen components for transport, stationary and mobile applications.

Important and pioneering work has been performed by SAE International for example with the Technical Information Report J2579 on vehicular hydrogen systems [1], which first among the standardisation bodies adopted a full performance-based standard to guarantee safety operation during the whole life of hydrogen pressurised components. The SAE J2579 standard consists mainly of an Expected-Service Performance Verification test and a Durability Performance Verification test of the hydrogen storage system.

In parallel to these standardisation activities, and often building upon them, a similar effort has been invested at national and international levels for the development of legally binding regulations. The European Commission has prepared a regulation for type approval of hydrogen-powered motor vehicles [2] with has been approved by the European Parliament and the Council in 2009 and, in 2010 [3], an additional, more technical document containing the implementing measures such as the individual tests required for the type approval. In this document all the tests and performance requirements needed to ensure safe and reliable function of all the components of a hydrogen-propelled vehicle are described in detail. Typical tests for high pressure components such as tanks are: burst test, bonfire test (resistance to fire), chemical exposure test, ambient temperature and extreme temperature pressure cycle tests, accelerated stress rupture test, impact damage test, leakage test hydrogen gas cycling test. According to the hydrogen gas cycling test, for example, the high pressure tank must be subjected without deterioration to 1000 hydrogen filling and emptying cycles which simulates the refilling at the refuelling station, followed by the fuel consumption during travel.

More recently, the United Nations Economic Commission for Europe (UN-ECE) has also concluded the drafting work for a Global Technical Regulation for Hydrogen Fuelled Vehicle [4], containing compliance tests for fuel system integrity, test procedures for compressed hydrogen storage and for electrical safety.

At the time of carrying out the tests proposed by these regulations codes and standards, there is a need of harmonization regarding technical implementation of test requirements and procedures. At the International Hydrogen Fuel and Pressure Vessel Forum 2010 technical experts presented information and data on testing and certification of storage tanks for compressed hydrogen and compressed natural gas [5]. There it was identified the need of having sound scientific/technical data available in order to establish a well justified scientific basis for globally harmonized test requirements and procedures for components certification. A round-robin testing program among international testing facilities was strongly recommended at Hydrogen Fuel and Pressure Vessel Forum 2010.

There is a need for collaborative pre-normative R&D and testing which must be peer-reviewed and results publicly available. There must be statistically reliable test results for essential components comprising the compressed hydrogen storage system of hydrogen fuelled vehicles, which in the case of on-board storage tanks may be difficult as the tests proposed in RCS are lengthy and obtaining sufficient number of tanks will be expensive. Furthermore, results from different test facilities must be independent and comparable [6].

Only after experience has been gained through collaborative R&D projects and tests it will be possible to establish laboratory qualification for high pressure hydrogen tank testing, including minimum laboratory testing capabilities (pressure, temperature, ramp rate, hold time, etc.) and the precision and accuracy required to perform an internationally harmonized test sequence.

Of particular concern for the JRC is the harmonisation of hydrogen gas cycle tests and permeation measurements. Since 2011commercial hydrogen tanks have been subjected in the JRC-IET's GasTeF facility to hydrogen filling-emptying cycles to investigate their long-term mechanical and thermal behaviour and their safety performance. JRC experimental activities are complemented by computational fluid-dynamics (CFD) modelling of the hydrogen filling process, by means of a numerical model previously developed and validated at the JRC-IET [7, 8]

The outcome of these activities is a set of experimental data which will be made publicly available as reference for safety studies and CFD validation. Furthermore JRC-IET is willing to contribute with such test data to inter-laboratory comparisons among other organisations involved in the same type of tests.

2. GASTEF DESCRIPTION

2.1. Purpose

The high pressure gas tank testing facility GasTeF is designed to carry out the following two experiments on high pressure gas storage tanks:

– Gas cycle test: it consists of tank filling and emptying cycles, in which the tanks are filled up to their nominal working pressure and then emptied, for a number of cycles required to simulate their lifetime. Typical filling times range from 3 to 5 minutes, while the emptying period can extend up to one hour. Helium, hydrogen or natural gas can be used.

– Gas Permeation: it consists of the measurement of gas leaks or permeation from the tank kept at its nominal working pressure for a long period of time (typically 100-500 hours). As for the gas cycle test, helium, hydrogen or natural gas can be used, but hydrogen is the one of major interest.

These two tests simulate the service conditions that a tank of a typical hydrogen vehicle experiences during its operative life: a quick filling at the hydrogen refuelling station, an idle or parking period and a slow emptying due to hydrogen consumption during driving.

2.2. Description

GasTeF consists of a half-buried concrete bunker with an attached gas storage area in open air. Fig. 1 shows a view of the facility. A more detailed description of the GasTeF system and its equipment can be found in [9].

Figure 1. GasTeF from outside, deliberately designed to look like a dune

The facility consists of the following major components:

- a gas compressor with its auxiliary equipment such as engine cooler and control unit,
- a hydrogen pre-cooler, to regulate hydrogen temperature before entering the test tank,
- a vessel where the tanks to be tested are placed together with the required experimental diagnostic equipment,
- a control system made of hardware and software components, for safety operation and data acquisition.

An outline showing some of these components is given in Fig. 2.

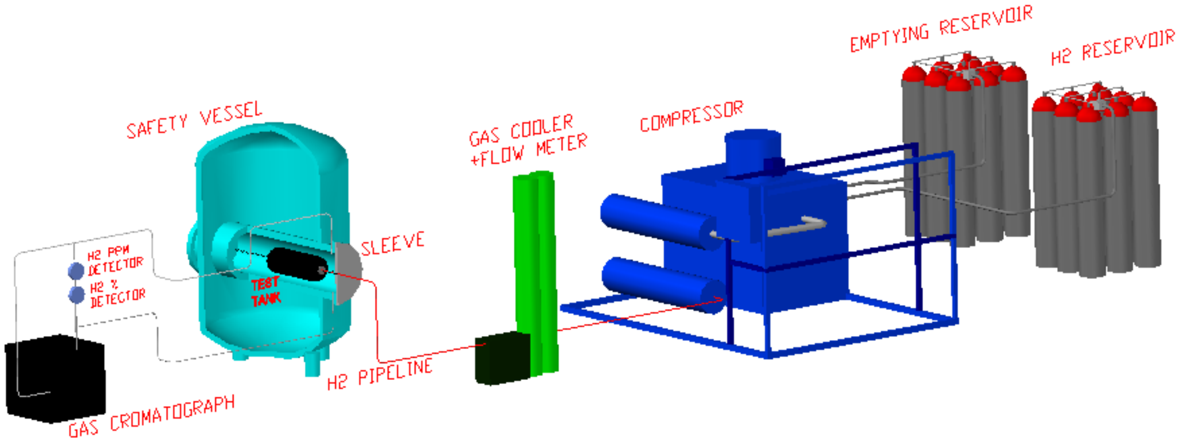


Figure 2. GasTeF schematic

2.3. Functioning

GasTeF has been designed to perform two of the standardised tests required for the approval of a high pressure storage tank of a hydrogen vehicle: namely the Hydrogen cycle test and the Permeation (and/or Leak) test.

Basically, the operations required to perform such tests can be reduced to only three: the pressurisation (filling) of the tank, a pressure holding phase and finally the decompression (emptying) of the tank. By means of the three basic operations and by varying starting and final pressures, environmental and gas temperatures and gas mass flow rates it is possible to tailor the experimental conditions to the objectives of the tests. For example, the hydrogen cycle test requires a high speed of filling, while the speed of emptying is not a critical parameter. A quick emptying is on the contrary required to simulate rapid decompression as it can occur during car maintenance. Finally, for the permeation the speed for the filling is not relevant, but the holding phase is extended for many hundreds of hours according to the requirement of the standard.

In all cases, filling is realised in two successive phases, namely a pressure equilibration phase followed by a gas compression phase. At the start of the filling, when the tank is empty, the full hydrogen storage is directly connected to the tank and the gas flow is driven by the pressure difference between storage and tank. When this pressure difference is reduced below a predetermined value, the compressor starts to pump further the hydrogen up to the nominal working pressure of the tank.

The same procedure is executed for the decompression (emptying) of the tank, with the difference that the first pressure equilibration occurs between the full tank and the empty hydrogen storage.

When gas conditioning is required to simulate hydrogen fuelling activities [10] or as stated in the standards SAE J2579 and ISO 15869 [11] for hydrogen container tests, a heat exchanger is used for pre-cooling the hydrogen prior to its introduction in the testing tank. The hydrogen cooler consists of high pressure stainless steel pipes formed in a coil which is submerged in liquid nitrogen. During the tank filling hydrogen passes through the cooler in contraflow to the nitrogen vapour and during the emptying the cooler is by-passed. The flowing hydrogen is cooled down to temperatures of -40 °C prior to fill the tank under test so that the filling is done in a short time (less than five minutes) without surpassing the 85 °C in the tank as established in the standards.

2.4. Hydrogen path

For modelling purposes is important to know the path that the hydrogen gas has followed before entering into the test tank. The following graphic (Fig. 3) depicts the gas flow within GasTeF, outlining how the hydrogen is passing from the exit of the compressor, passing to a flow control valve and the hydrogen-cooler to enter the test tank. The compressor and the test installations are connected with high pressure stainless steel piping. The gas line at the first part of the path (blue line in Fig. 3) from the compressor exit has an internal diameter of 12 mm whilst the second part (green line in Fig. 3) until the inlet of the tank is a pipe of 5 mm internal diameter. The pressure value at the final part of the path is given by a pressure transducer (PT-7 in Fig.3) placed in the gas line at 1270 mm from the tank inlet.

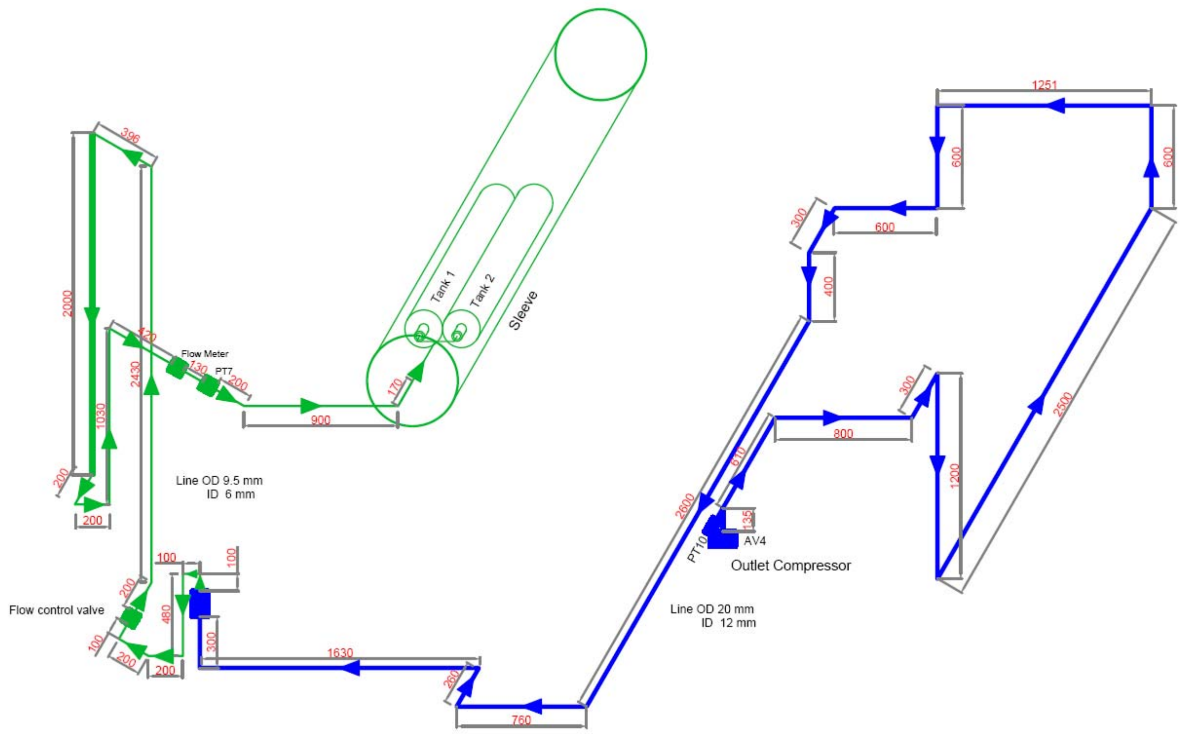


Figure 3. GasTeF hydrogen flow path

Test performed with a pressure transducer placed immediately before the tank inlet has shown that the pressure measured does not differ from that of the PT-7 point. The actual pressure in the tank is measured by means of a pressure transducer placed at the tank rear side. Also this pressure does not significantly differ from the pressure at the tank inlet as can be seen in Fig. 4. This figure shows the pressure evolution during the filling part of a cycle test and it can be noted that at the beginning of the filling the tank is empty while there is some hydrogen remaining in the pipeline from the previous cycle. This difference disappears as soon as the pressures in the tank and line are equalised. In Fig. 4 can also be observed how the oscillation in pressure due to the compressor work becomes more noticeable at the end of the filling.

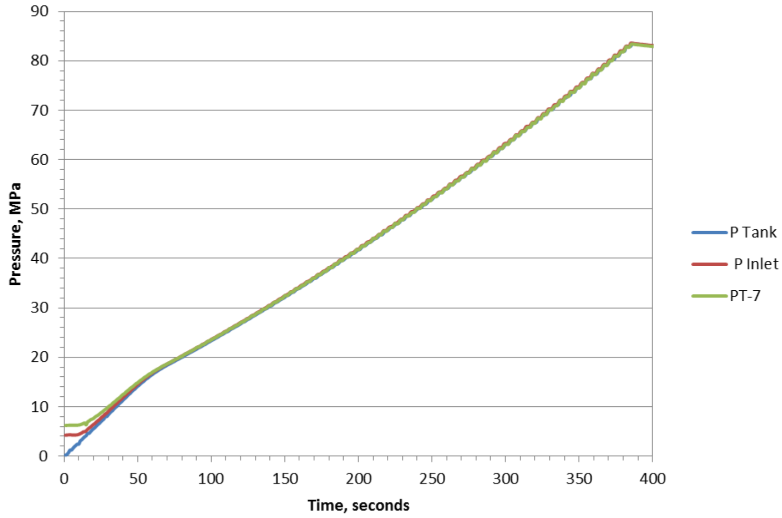


Figure 4. Comparison of pressures measured at different locations

The temperature of the gas is measured at different points along the gas path, namely at compressor exit, at the cooler exit in the same location of PT-7 and approximately 250 mm before the tank inlet.

2.5. Tanks environment during tests

Tanks to be tested are installed inside a cylindrical chamber called the "sleeve", located horizontally inside the safety test vessel, see Fig. 2. The sleeve has 500 mm diameter and 2050 mm length and is filled with an inert gas (helium or nitrogen) that continuously flows at an adjustable rate between 350-500 Nml/min.

The sleeve is the real experimental area of the facility, where the tank leaks and permeation are measured and where the tank environmental temperature is controlled and measured. The sleeve is equipped with two hydrogen detectors: a wide range detector (0-10%) and a higher accuracy detector active in the range 0-2000 ppm of hydrogen. In addition a gas chromatograph may be used for accurate measurements of H_2 or He in the sleeve.

The temperature of the sleeve can be adjusted from ambient conditions to 85 °C and a fan is used to move the sleeve's gas when test conditions require homogenisation of temperatures in the surroundings of the testing tank. Due to the configuration of the test facility, the sleeve temperatures are kept quite stable during the test campaigns.

3. DATABASE EXPERIMENTAL DESCRIPTION

3.1. Tested Tanks

To date three different 70 MPa Nominal Working Pressure hydrogen tanks have been tested in GasTeF: a type 3 of 40 litres volume, a type 4 of 29 l and a 19 litres type 4. In Table 1 the characteristics of the tanks are given.

The used end plugs have a gas inlet nozzle of 3 mm diameter. In some of the experiments a 1 mm thermocouple has also been inserted at the tank inlet.

Table 1. Tested tanks at GasTeF

	Type 4 19 l	Type 4 29 l	Type 3 40 l
Materials Liner	HDPE	HDPE	AA
End Bosses	AA	SS	AA
Composite shell	CFRE	G&CFRE	CFRE
Vessel mass (Kg)	18.3	32.9	41.5
Storage volume (L) (at 700 bar)	19	28.9	40
H2 capacity (Kg) (with fill density of 40.22 Kg/m3)	0.76	1.16	1.60
Unpressurized dimensions (mm)			
External length	904	827	920
External diameter Internal diameter	228 180	279 230	329 290

HDPE: High density polyethylene, CFRE: Carbon fibre-reinforced Epoxy, G&CFRE: Glass and carbon fibre reinforced Epoxy, AA: Aluminium Alloy, SS: Stainless Steel

3.2. Measuring instrumentation

Tanks are instrumented with eight thermocouples and with different resistance temperature detectors (RTD) arranged as depicted in Fig. 5. The temperature detectors (four in most of the cases) are fixed at the outer surface and the eight thermocouples are placed inside the tank. The thermocouples 7 and 8 are inserted through the gas inlet opening whilst the other internal thermocouples are mounted on a special tree shape array designed at JRC-IET, which is introduced at the rear of the tank (opposite to the gas inlet) and can be axially displaced so that the distance of the thermocouples to the gas inlet can be adjusted. The thermocouple number 5 acts as reference for all temperature measurements and remains therefore in a fixed position even if the array's location is adjusted. The external RTD T_{Top} is placed on the tank surface in correspondence to the reference thermocouple 5.

The thermocouples have a diameter of 1 mm and are of type K, capable of measuring in a range of -200 to 1250 °C with an uncertainty of 2.2 °C. Their response time in air moving at 2 m/s is 3 seconds to reach 50% of the instantaneous temperature change and 10s to reach the 90%. The RTD has a nominal resistance of 100 Ohms at 0 °C and are capable to measure temperatures in a range of -100 °C to 550 °C with a maximum deviation of 1.25 °C.

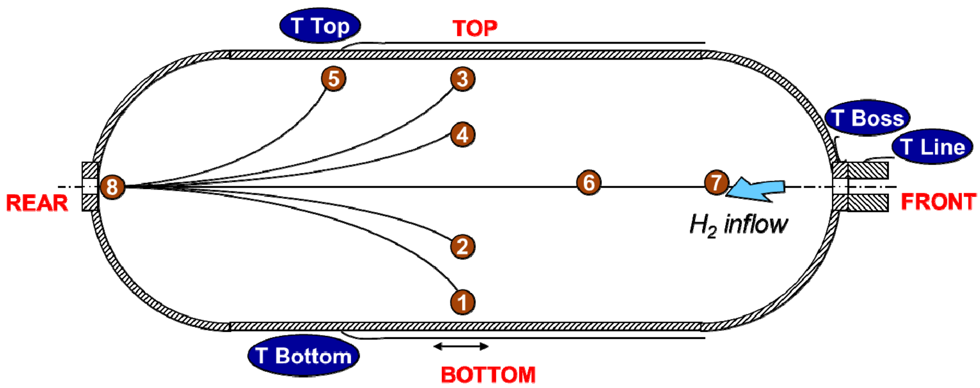


Figure 5. Arrangement of the temperature measurement instrumentation in the tanks

The gas pressures at the inlet/outlet and inside the tank are measured using pressure transducers. To be able to measure the whole pressure range from 1 to 70 MPa with the required accuracy, two different transducers are used, one calibrated for the low end of the pressure range, the other for the high end. For the high range pressure transducer (0 to 70 MPa) the error is 5 % (full scale) for pressures below 10MPa and 0.64 % at 70 MPa whereas for the transducer calibrated for low pressures, 0 to 2.5 MPa, the error is 0.4 %. The time interval for pressure and temperature data logging is 0.6 seconds.

3.3. Test Conditions

A considerable number of fast filling and hydrogen cycle tests have already been carried out in GasTeF. Several starting and end pressures have been considered and different pressure rates are achieved. Moreover temperature evolution measurements are continued during the holding phase, to follow the stabilisation of pressure and temperatures and during emptying to examine the tank behaviour while de-fuelling. In this paper only results from the filling part are analysed and presented. The following tables show the test conditions for: a) type 3 40 l, Table 2, b) type 4 29 litre volume, Table 3, c) type 4 19 litres, Table 4 and d) fillings with pre-cooled hydrogen of type 4 29 l tank, Table 5. The tests on type 4-19 litres are conducted within the frame of the project HyCOMP funded by the FCH-JU [12].

As it can be seen in the tables for the different filling conditions several Average Pressure Ramp Rates (APRR) have been achieved. For the most typical filling conditions (e.g. 2 – 72 MPa) more than one APRR is applied, which is shown in the table by the APRR’s range. Some of the obtained APRR are unrealistic from the point of view of hydrogen vehicle refuelling however they are interesting when studying the evolution of temperatures during tank filling.

In the tables the tank internal temperature (gas temperature) before the filling starts is also shown. The most of the filling are done when the tank is in steady-state condition at room temperature but, as can be noted in the tables, some of the fillings are part of a cycling sequence and are starting after the decompression phase, hence the temperature of the gas remaining in the tank is low, even reaching negative values. Common to all tests is that they have been performed with the sleeve maintained at room temperature.

Table 2. Test conditions type 3 tank 40 litres

FILLING CONDITION	APRR (MPa/min)	TANK INNER TEMPERATURE "ad initio" (°C)
0-78 MPa	16.5	19.88
0-79MPa	33.8	17
2-78 MPa	5.5 – 18.6	-0.6 – 18.3
2-79 MPa	24.9 & 30.2	20
2-80 MPa	30.7	4.5
2-85 MPa	15.1 & 16.2	-1.2 & -0.2

Table 3. Test conditions type 4 tank 29 litres

FILLING CONDITION	APRR (MPa/min)	INITIAL TANK TEMPERATURE (°C)
0-30 MPa	17.4	21.4
0-35 MPa	16	22.9
0-71 MPa	36.3	21.8
0-72 MPa	12.3 - 19.1	9 - 27
0-78 MPa	24.7	18.49
1-81 MPa	23.8	-5.4
2-30 MPa	0.7 - 39.8	14 - 21
2-35 MPa	20.7 & 23.7	12
2-36 MPa	26.5	14
2-71 MPa	36.5 - 37.1	10.2 - 13.4
2-72 MPa	13.7 - 22.4	19.8 - 24.1
2-77 MPa	17.5 - 17.9	-3.4 – 13.8
2-80 MPa	18.3	17 - 23
2-81 MPa	18.3	7.6
4-72 MPa	13.1 - 15	3.7 – 19.2
15-69 MPa	7.7 – 32.8	11.4 -33.9

Table 4. Test conditions type 4 tank 19 litres

FILLING CONDITION	APRR (MPa/min)	INITIAL TANK TEMPERATURE (°C)
0-13.5 MPa	8.3	17.6
0-50 MPa	7	24
0-71 MPa	9.8	21.6
0-73 MPa	8.1 & 8.4	21.7
0-76 MPa	8.7	13.1
2-12 MPa	6.7	17.5
2-22 MPa	11.5	2.9
2-34 MPa	9	22.5
2-50 MPa	6.3	22.1
3.3-14.6 MPa	11.3	12.4 &11.1
3.3-36 MPa	10.1	1
3.3-83.4 MPa	14.6	-1.9
3.3-84.1 MPa	14.7	-3.1
3.3-84.5 MPa	11.4 – 18.1	-1.9 – 1
7-14 MPa	10.7	21.2
10-22 MPa	9.2	0
20-40 MPa	8.6	23.8
20-84.5 MPa	10.7-11.3	23.5
28-76.4 MPa	8.8	20.9
35-76.4 MPa	9.2	11-16

Table 5. Test conditions type 4 tank 29 litres with gas pre-cooling

FILLING CONDITION	APRR (MPa/min)	GAS TEMPERATURE (°C)	INITIAL TANK TEMPERATURE (°C)
2-70 MPa	15.5 & 15.8	-30	-5.2 & -13.5
2-77 MPa	17.2	-6.3	-1.7
2-78 MPa	16.5	-42.3	12.7
2-78 MPa	22.2	-30 & -31	15 & 0.44
2-78 MPa	23.5	-4.7	-8.8

In total the database has 109 entries for tests conducted on type 3 and type 4 tanks. The Fig. 6 displays the amount of tests done on type 4 tanks for each filling condition. As said before for the most typical tank filling conditions a bigger number of tests has been performed and are available in the database. For example the Fig. 7 shows the distribution of the test carried out with the type 4 of 29 l for which the initial pressure of the tank was in the range 2-4 MPa.

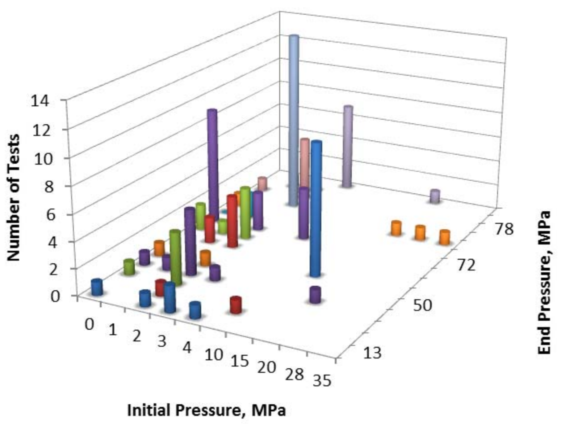


Figure 6. Matrix of tests made on type 4 70 MPa tanks

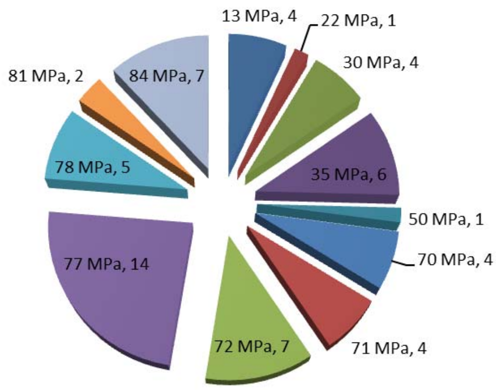


Figure 7. Number of filling tests of a type 4 29 l tank with initial pressures of 2-4 MPa

Figure 8 summarises fifteen tests conducted on the type 3 tank, also in this case the most of the tests are done for the filling condition 2 – 78 MPa.

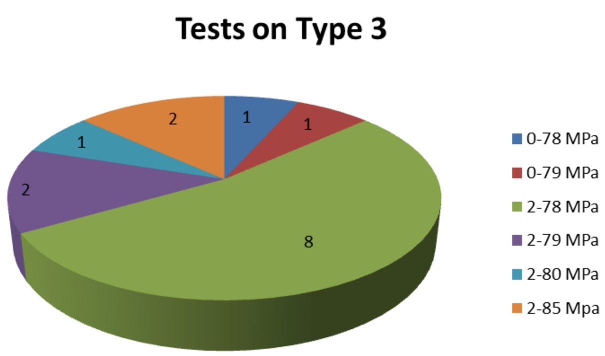


Figure 8.Tests made on type 3 tank

4. DATABASE ASSESSMENT: EXAMPLE OF RESULTS

4.1. Cycling tests

Fig. 9 gives an example of a typical cycle sequence performed in GasTeF. Each hydrogen cycle shown in Fig. 9 consists on a filling of the tank from 3 to 84 MPa, a holding at high pressure during 16 minutes and a slow tank depressurisation. For three of these cycles the evolution of the pressure and of the gas temperature inside the tank is depicted in Fig. 9. After filling, all temperatures but these measured at the gas inlet (TC7) and at the rear ends (TC8) which are influenced by the material of the boss, are equalized. After emptying, however, stratification in gas temperature is significant and a difference of 27 °C from bottom to top of the tank is observed.

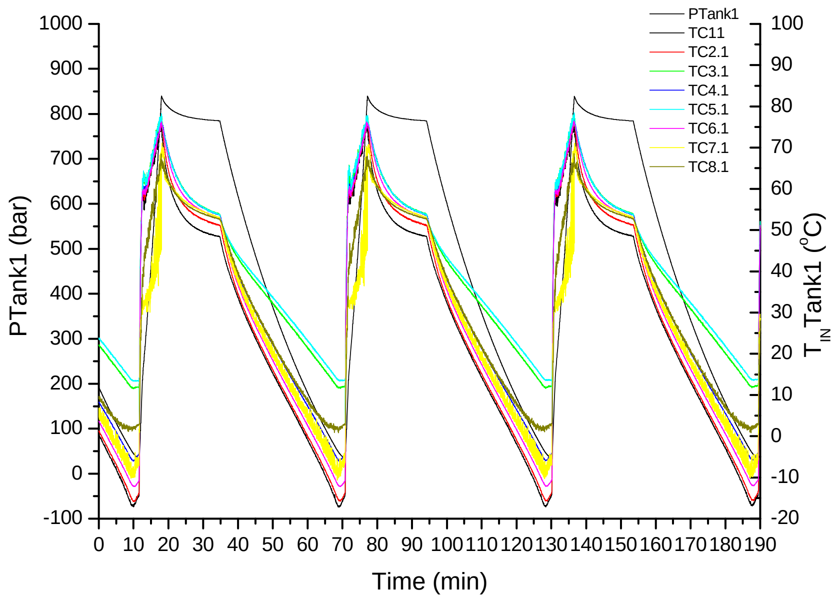


Figure 9.Example of filling-holding-emptying cycle

In the Fig. 9 it can be also noted that the temperature values repeat along the cycles. In fact, after the first 2-3 cycles both the temperature in gas lines and in the tank environment stabilize and all the cycles exhibit the same profile for pressure and temperature evolution. Table 6 shows the statistics for a sequence of 350 cycles; cycles replicate with little standard deviation.

Table 6. Statistics sequence of 350 cycles performed with a type 4 19 l tank

	MEAN	STANDARD DEVIATION
Filling Time, (s)	310.4	3.3
Filling Initial P (MPa)	3.28	0.10
Filling Final P (MPa)	84.44	0.82
Filling Initial T (°C)	16.9	0.21
Filling Final T (°C)	83.1	0.63
PT7	83.66	1.22
Boss Initial T Filling (°C)	11.3	0.09
Boss Final T Filling (°C)	52.6	0.09
Emptying Time (min)	33.6	0.09
Emptying Initial P (MPa)	76.91	0.42
Emptying Final P (MPa)	2.98	0.08
Emptying Initial T (°C)	54.5	0.15
Emptying Final T (°C)	11.4	0.09

4.2. Repeatability

In order to assess the repeatability of the results, 12 tests with the same filling conditions (2–76.9 MPa at 17.8 MPa/min APRR, without hydrogen pre-cooling) using a 29 litre type 4 tank have been separately performed. Table 7 shows the statistical evaluation of these tests. As it can be noted, even if the tank initial temperature is slightly different for the various tests the achieved final pressure and the temperature increases are well reproduced in each test.

Table 7. Statistics for filling tests 2-76.9 MPa, type 4 29 l tank

	MEAN	STANDARD DEVIATION
Filling Time, (s)	253	1.4
Initial P, (MPa)	1.99	0.36
Final P, MPa	76.89	0.91
Tank averaged Initial T, (°C)	11.2	3.7
Tank averaged Final T, (°C)	86.9	2.9
Increase in temperature, (°C)	75.6	0.9

4.3. Measurement of tank temperature in the bosses

In the hydrogen gas cycling test defined in the ISO/TS 15869:2009 standard [11], it is specified that temperatures during the test shall be monitored using a thermocouple attached to the metal end boss at both ends of the fuel tank. The temperature evolutions during a hydrogen cycle measured in the front boss and the maximum temperature inside the tank are depicted in Fig. 10. A comparison between responses of bosses made of different material (aluminium and steel) to the temperature change in the gas tank is also shown in Fig. 10. A more detailed analysis on the correlations between tank internal and external temperatures is presented in [13].

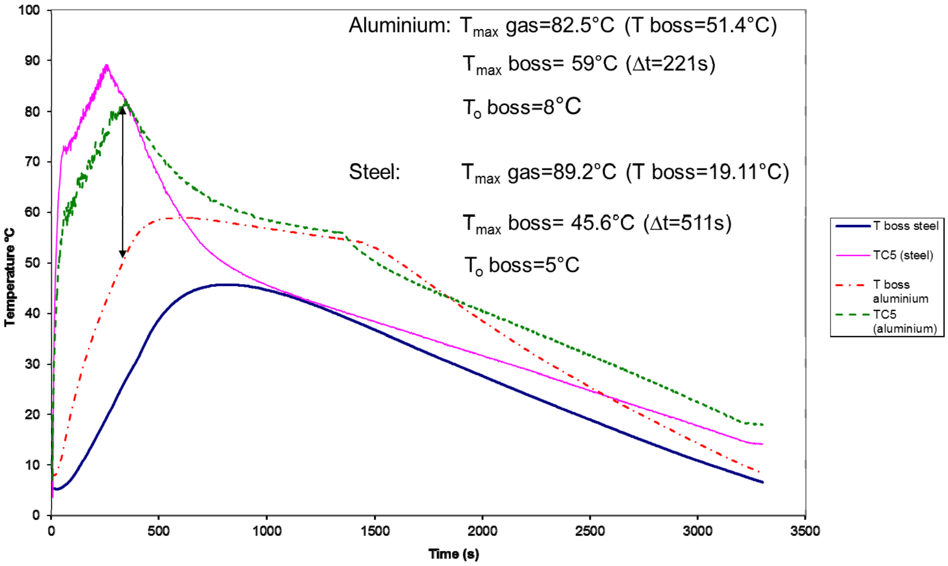
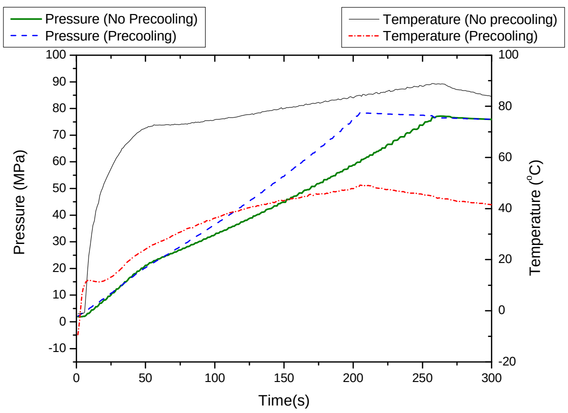


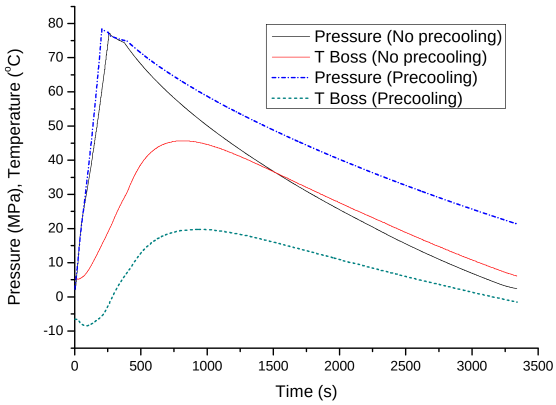
Figure 10. Influence of the boss material on tank temperature assessment

4.4. Fast filling with pre-cooled hydrogen

Fast filling with cooled hydrogen has been conducted in GasTeF with the aim of demonstrating the pre-cooler capability, for this reason only 9 filling tests of a type 4 29 litres tank with cool hydrogen at -42 to -30 °C are currently available in the database. As an example in the Fig. 11 it is presented a filling from 2 to 78 MPa with hydrogen at -30 °C and for comparison purposes a similar filling with gas at ambient temperature is included in the graphs. Despite of the difference in the APRR (22.2 MPa/min for the filling with cool hydrogen against 17.5 MPa/min for the filling with gas at ambient temperature) which makes difficult any quantitative comparison, the Fig.11 (a) shows how the increase in the tank internal temperature is much smoother when cooled hydrogen is used. Looking at the temperature evolution for the filling with pre-cooled hydrogen (dotted line in Fig. 11 (a)) it is observed a slight decrease in the temperature from 11.95 to 11.2 °C, 10 seconds after the begin of filling, probably this effect is due to the start of compressor pumping gas, injecting a "first shot" of very cool hydrogen in the tank. Later this effect is compensated by the heat of compression and the gas temperature continues to increase reaching, in this case, 49.2 °C. This effect of very cool hydrogen shot once the compressor starts pumping is also sharply detected by the thermocouple placed in the front boss (dotted line in Fig. 11 (b)).



(a)



(b)

Figure 11. Example of fast fillings with and without pre-cooling in terms of tank average temperature (a) and of temperature measured in the tank front boss (b)

The SAE J2601 standard establishes the protocol guidelines (algorithm) for fuelling of gaseous hydrogen at 35 MPa and 70 MPa into on-road passenger vehicles [10]. When no data communication between the vehicle tank and the refuelling station is available the SAE J2601 defines a "tables-based" approach. This approach uses the ambient temperature measured at the station, the initial measured pressure storage tank and the capacity of tank to “look-up” the average pressure ramp rate and target fill pressure.

Notwithstanding the differences between GasTeF and a hydrogen refuelling station regarding the way of filling the hydrogen tank, the results of the fast filling tests with pre-cooling have been checked with the SAE J2601 tables.

The test conducted with hydrogen at -42 °C, see Table 5, started at 2 MPa but the filling was continued until 78 MPa with an APRR of 16.5 MPa/min. Checking the SAE J2601 Table 8-1 for 20 °C ambient temperature the pressure target for our filling condition should have been 73.2 MPa with an APRR of 28 MPa/min; in fact even if the filling is carried out at smaller APRR than 28 MPa/min the state of charge (SoC) of the tank results 101.6 %.

The following check is made looking at the SAE J2601's table F-2 (hydrogen dispensed at -20 °C) since in GasTeF experiments the initial tank (inner gas) temperature is known. The results are summarised in the Table 8. Regardless of GasTeF's filling tests being performed with hydrogen pre-cooled at -30 °C the applied pressure rating and the achieved SoC for the 70 MPa fillings are in good agreement with the APRR determined by the SAE J2601. For the fillings to 78 MPa the APRR of the test is substantially higher than those of the J2601 however the tank has not been over-charged because the hydrogen temperature is lower than the -20 °C of the table F-2. Looking at the Table F-1, for hydrogen pre-cooled at -40 °C, the corresponding APRR is 28.2 MPa/min, thus in our tests the higher gas temperature and greater end pressure are compensated by a slower filling.

Table 8. Filling with pre-cooled hydrogen at -30 °C test results and validation with SAE J2601

PRE-COOLING TEMP. (°C)	TANK INITIAL TEMP. (°C)	END PRESSURE (MPa)	APRR JRC Tests (MPa/min)	APRR in J2601 Table F-2 (MPa/min)	SoC** (%)
-28.8	-5.2	70.2	15.6	*16.06	94.6
-29.6	-6.3	70.4	15.8	*16.39	93.8
-30	-13.5	70.3	15.5	17.5	95.2
-29	-8.4	70.5	15.5	*17.02	95.3
-31	0.44	78.1	22.2	14.5	99.8
-30.2	15	77.9	22.3	10.9	97.8

* Extrapolated

** Calculated using the equation in the SAE J2601

** Note that the tank initial pressure is 2 MPa for the considered experiments

5. CONCLUSIONS

The high pressure gas tank testing facility GasTeF is designed to carry out the hydrogen cycle test and the permeation test according to the procedures prescribed by the European Regulation on type-approval of hydrogen vehicles and by other international standards such as ISO and SAE. GasTeF results are used to assist technology developments, but also to validate and improve safety and performance requirements for hydrogen tanks for transport applications.

A considerable number of fast filling and hydrogen cycle tests have been conducted in GasTeF. In total the database has 109 entries for tests conducted on type 3 and type 4 commercial tanks. The database contains the results of temperature measurement for many filling and emptying conditions representative of the operation of hydrogen storage tanks.

The GasTeF data will be made publicly available as reference for safety studies and CFD validation. Furthermore JRC-IET is willing to contribute with such test data to inter-laboratory comparisons among other organisations involved in the same type of tests.

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