ANALYSIS OF OUT-OF-SPEC EVENTS DURING REFUELING OF ON-BOARD HYDROGEN TANKS

de Miguel, N.[1], Acosta, B., Moretto, P., Harskamp, F.

Directorate for Energy, Transport and Climate, Joint Research Centre (JRC), European Commission, P.O. Box 2, Petten, The Netherlands, [1] nerea.de-miguel-echevarria@ec.europa.eu,

ABSTRACT

For refueling on-board hydrogen tanks, table-based or formula based protocols are commonly used. These protocols are designed to achieve a tank filling close to 100% SOC (State of Charge) in s safe way: without surpassing temperature (-40°C to 85°C) and pressure limits (125% Nominal Working Pressure, NWP). The ambient temperature, the initial pressure and the volume category of the (compressed hydrogen storage system, CHSS are used as inputs to determine the final target pressure and the pressure ramp rate (which controls the filling duration). However, abnormal out-of-spec events (e.g. misinformation of storage system status and characteristics of the storage tanks) may occur and result in a refueling in which the safety boundaries are surpassed. In the present article, the possible out of specification (out-of-spec) events in a refueling station have been analyzed. The associated hazards when refueling on-board hydrogen tanks have been studied. Experimental results of out-of-spec event tests performed on a type 3 tank are presented. The results show that on the type 3 tank, the safety temperature limit of 85°C was only surpassed under a combination of events; e.g. an unnoticed stop of the cooling of the gas combined with a wrong input of ambient temperature at a very warm environment. On the other hand, under certain events (e.g. cooling the gas below the target temperature) and in particular under cold environmental conditions, the 100% SOC limit established in the fuelling protocols has been surpassed.

Hydrogen safety, on-board tanks, refueling protocols, out-of-spec events

1. INTRODUCTION

Since hydrogen technology and infrastructure are both progressing fast, car manufacturers are already selling FCEVs [1]. These vehicles use gaseous hydrogen which is stored in tanks at high pressures (35 MPa or 70 MPa Nominal Working Pressure, NWP). The body of these tanks is made of either a metal (on type 3) or a polymer liner (on type 4) which is then reinforced with a composite wrapping (carbon fibres embedded in a resin) to withstand the high pressures [2]. One or more of these tanks together with the components that prevent hydrogen escaping from the system (the check valve, shut-off valve and the thermally activated pressure relief device) constitute the Compressed Hydrogen Storage System, CHSS of the hydrogen vehicle [3].

To refuel hydrogen vehicles with an acceptable duration (comparable to that of conventional cars), the gas should be compressed in the CHSS to a high pressure in a short time. This causes an increase of the gas temperature inside the tank [4]. The State of Charge, SOC (1) is defined as the ratio between the density of the gas at a given temperature and the density of the gas at the NWP and 15°C temperature. In order to get a SOC as close as possible to 100%, the increase of gas temperature is compensated with a higher final pressure target.

$$SOC(\%) = \frac{\rho_{H2}(P,T)}{\rho_{H2}(NWP, 15^{o}C)} \cdot 100, \quad (1)$$

For safety reasons, regulations and standards for the type approval of hydrogen powered vehicles have established that the hydrogen temperature inside the tank shall be in a range between -40°C and +85°C whereas the pressure cannot surpass 125% the NWP [3], [5]-[7]. This maximum operating pressure, MOP, is the highest pressure that is expected from a component or system during normal operation (including starts, stops and transients) [5]. This is the pressure from which hydrogen at a temperature of +85°C would settle at the NWP (at a temperature of 15°C) [8]. Taking these boundaries into account fueling protocols for light duty vehicles are established in the SAE J2601:2016 standard [7]. Fueling protocols are designed such that the maximum operating temperature in the CHSS is not exceeded at any point during the filling. To perform the fueling in a reasonable time, the use of pre-cooled hydrogen is required. However, tank overfilling (SOC > 100%) should also be avoided.

The ISO/TS 19880-1:2016 [8], describes technical specifications to be meet by gaseous hydrogen fueling stations. During the refueling, the hydrogen temperature and pressure are monitored and controlled by the dispenser. The amount of dispensed hydrogen should be also metered and the ambient temperature monitored by the fueling station. Figure 1 shows a fueling station dispenser connected to the CHSS of a hydrogen vehicle. A fueling hose assembly should contain a breakaway, a hose and a nozzle. The breakaway is a device installed on a dispensing hose that separates when a given pull force is applied (e.g. a vehicles diving away) and closes the flow of hydrogen to prevent gas leakage. As described in the ISO technical specification [8], the temperature and pressure sensors measuring the fuel delivery conditions at the station dispenser shall be located as close as possible to the hose breakaway.

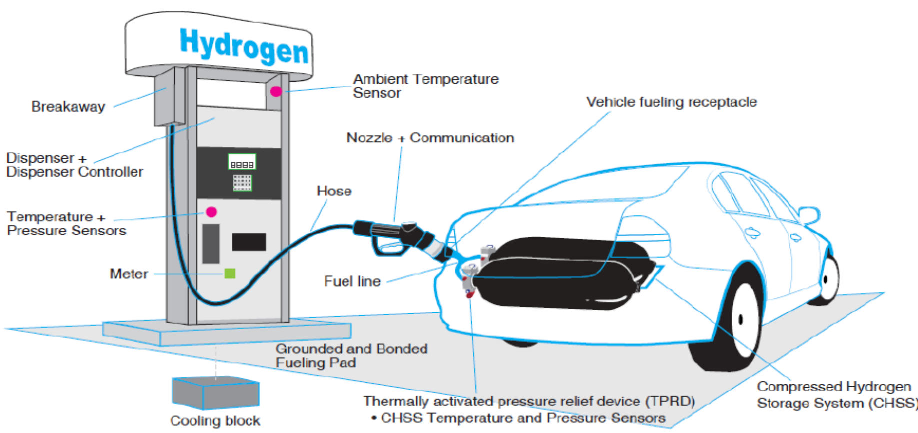

Figure 1. Schematic of station dispenser with FCEV CHSS (from ISO/TS 19880-1:2016 [8])

The refueling consists of a startup time which begins when the nozzle is connected to the CHSS and includes a connection pressure pulses [7]. The initial vehicle tank pressure is detected with a first pressure pulse. A second pressure pulse is used to estimate the volume of the vehicle tank, and to detect any leaks [9]. The fueling subsequently starts when the gas flows into the storage system. During this period, the pressure rises and the temperature of the gas inside the hydrogen tank(s) increases. The final stage is the shutdown which occurs after the hydrogen gas has stopped flowing and ends when the nozzle is disconnected. The refueling is categorized by three different parameters: (1) the CHSS capacity category, (2) the station's fuel delivery temperature category and (3) the dispenser pressure class.

The fueling nozzle may contain an Infrared Data Association, IrDA, communication system with a receiver which communicates with the transmitter of the vehicle. The SAE J2799:2014 [10] communication hardware and software can be used for this purpose. When no valid data exists from the vehicle to the fueling station dispenser, the refueling is done with non communication. Moreover, the refueling can be performed by two different approaches: through look up tables or by a formula based approach [9]. The ambient temperature and the initial pressure of the tank are input variables. The look-up tables give a fixed end of fill target pressure and pressurization rate. Using the formula based approach; the end pressure and the ramp rate are adjustable during the filling.

When refueling a CHSS using a fueling protocol, there could be out of specification (out-of-spec) events e.g. misinformation of storage system status and characteristics of the storage tanks, that might result in the temperature, pressure or charge safety thresholds being surpassed. In the present paper, an analysis of the safety considerations for refueling on board hydrogen tanks and of the possible consequences of the out-of-spec events has been done. We have already performed tests on type 4 tanks where under some conditions over-temperature (T > 85°C) inside the tank was confirmed. However, the exposure time of the tank materials to this temperature was short and the temperature at the hydrogen tank wall (in between the liner and the composite) remained below the 85°C threshold [11]. The SAE J2601:2016 [7] does not make any difference on the tank type of the CHSS. Nevertheless, due to the different thermal properties of the two normally used on-board hydrogen tanks (type 3 and type 4) [4], the safety concerns of each tank are different. In the present paper, experimental tests have been performed on a commercial type 3 tank to assess specifically possible effects that the out-of-spec events could have on this type of tank, in particular under cold environmental conditions.

2. ANALYSIS OF THE POSSIBLE OUT-OF-SPEC EVENTS

During the hydrogen refueling process, there could be a number of circumstances that result in one or more of the specifications given in the protocol not being fulfilled. These out-of-spec events could lead to dangerous situations where the temperature and pressure safety boundaries are surpassed. In the following, three possible events have been studied:

1. Wrong selection of the refueling parameters. The station uses wrong information (e.g. the Programmable Logic Controller, PLC fails) leading to choosing a wrong look up table. The refueling is categorized based on:

   1) The CHSS capacity class: 2-4 kg, 4-7 kg or 7-10 kg.
   2) Fuel delivery temperature category: T40 (-40°C to -33°C), T30 (-33°C to -26°C) and T20 (-26°C to -17.5°C).
   3) Dispenser pressure class: H35 (35 MPa) or H70 (70 MPa).

2. Technical failures at the refueling station e.g. failure of the pressure and/or tempertature sensors of the station or failure of the pre-cooling system (cooling above or below the target temperature).

3. Wrong inputs on the look up tables result of misreading of the ambient temperature, T_{Amb} and/or the initial pressure of the tank, P_0.

These circumstances or a combination of more than one of them would lead to a wrong selection of target Average Pressure Ramp Rate, APRR or to a wrong final pressure, P_F. When the target presurization rate is higher than what it should be, the temperature of the gas inside the tank may go above +85°C. On the contrary, when the pressurization rate is slower and the final pressure higher, there is the risk of overfilling the tank (>100% SOC) or even surpassing the MOP when the temperature of the gas inside the tank is equilibrated with the environmental temperature. Compressed hydrogen storage vessel materials are qualified to +85°C [3]. However, since the gas bulk temperature is higher than the material temperature [12], [13], there is a possible margin within the fueling limit of +85°C.

Table 1 summarizes several out-of-spec events that could happen in a refueling station and the safety risks associated to them.

Table 1. Summary of the considered out-of-spec events, specific scenarios and the safety concerns involved.

Out-of-spec events		**Scenario**	**Safety concern**
1) Wrong selection of the refueling parameters or 2) a technical failure at the refueling station	Wrong selection of the CHSS capacity class	1. Fueling a smaller tank	Over T (at high T_{Amb})
	Wrong selection of fuel delivery temperature category or Failure of the pre-cooling system	2. Fueling with warmer gas	Over T
		3. Fueling with colder gas	Over filling
	Wrong selection of the dispenser pressure class	4. Fueling a tank with lower NWP	Over P & Over filling
2) a technical failure at the refueling station or 3) Wrong inputs on the look up tables	Deviation of the ambient temperature sensor or Wrong input of the T_{Amb} on the look up tables	5. Fueling in a warmer environmental temperature	Over T
		6. Fueling in a colder environmental temperature	Over filling
	Wrong measurement of the initial tank pressure or Wrong input of the P_0 on the look up tables	7. Fueling with higher initial tank pressure	Over filling (at low T_{Amb})

The scenario (1) considers a wrong chosen CHSS capacity. When the tank being filled is smaller than the targeted one and at an ambient temperature above 10°C, the APRR given in some of the look up tables of the SAE J2601 will be higher than what it should be, which could result in an over-temperature inside the tank.

The next situation considered (2) is when the chosen pre-cooling category on the look up tables is for colder gas than the one on the dispenser (so the filling is done faster). It can also happen that the supplied hydrogen is warmer than the expected temperature window of the station because the cooling system failed. These scenarios could eventually lead also to an over-temperature inside the tank.

The case (3) is the other way around, when the chosen pre-cooling category on the look up tables is for warmer gas than the actual pre-cooling capacity of the station (so the filling is done slower). Similarly, when the supplied hydrogen is colder than the expected temperature window of the station. These assumptions could result in an overfilling of the tank (SOC > 100%).

In the scenario (4), the chosen pressure class is wrong; the station fills a 35 MPa tank with a 70 MPa target. The filling speed will be similar or even lower and the target pressure will be higher, resulting in an overpressure (and consequently overfill) inside the tank. However, as it is going to be discussed in the next chapter, this situation is avoided by designing the station dispensers with different separate nozzles [14] for each NWP system.

The next situations considered are when the ambient temperature sensor fails or when the input of the ambient temperature on the look up tables is wrong. In scenario (5), the ambient temperature is higher than the targeted one. The final pressure will be lower but the filling is going to be done at a much higher speed which could lead to an over-temperature inside the tank.

On the contrary, in scenario (6) the ambient temperature is lower than the targeted one and the tank could result more filled than how it should be.

In the SAE J2601 protocols, the pressurization rate does not depend on the initial pressure. As reflected in scenario (7), at very low ambient temperatures and when the real initial pressure inside the tank is higher than the targeted one, the final pressure is going to be significantly higher and this could lead to an overfilling of the tank.

Combinations of these events could also happen in a refueling station.

2.1. Safety considerations for refueling

As already mentioned, for the dispensing of the hydrogen, the fueling station should prevent the allowable limits of temperature, pressure and state of charge (SOC) for the vehicle CHSS from being exceeded. The ISO/TS 19880-1:2016 [8] recommends the minimum design characteristics for safety and, where appropriate for performance of public and non-public fueling stations that dispense gaseous hydrogen to light duty land vehicles (e.g. Fuel Cell Electric Vehicles).

More specifically, the hydrogen stations should include measures for the avoidance of different identified hazards. A risk assessment (process of risk identification, analysis, evaluation and mitigation) allows station owners and designers to flexibly define station-specific measures that achieve an equal or better level of safety to those of prescriptive rules. Among other measures:

1) On the station side, there is an automated dispensing control system (e.g. through a PLC) for performing the fueling, as well as fault detection and management procedures. Stations should use the SAE J2601 fueling protocols and for communication fuelling, the SAE J2799 software. Any other protocols should be approved and validated to confirm compatibility and robustness. The station also has an over pressure protection device such as a pressure relief device(s) or equivalent to protect against over pressurization of the dispenser and the vehicle.

2) The ambient temperature and the temperature, pressure and mass flow rate of the hydrogen fueling should be monitored. The sensors should be placed in a proper location; e.g. the temperature sensor of the dispensed gas, as close as possible to the hose breakaway. The ambient temperature sensor shall be placed in a location in order to give an accurate reading and should not be located in the direct sunlight, or influenced by other thermal sources. The ambient and fuel delivery temperature sensor tolerance shall be within +/- 2°C. The pressure sensor tolerance shall be within 1% full scale.

3) Station dispensers may be designed with separate nozzles to fuel vehicles to 35 MPa and/or 70 MPa nominal working pressures. The refueling connection devices should be fitted according to appropriate ISO 17268:2012 pressure class rating according to the application [14].

4) The fueling protocol should be appropriate for the vehicle CHSS capacity (e.g. 2 kg to 10 kg for 70 MPa SAE J2601).

5) The station should have a fault detection and management procedure. The station dispenser shall terminate the fueling within 5 seconds (but not necessarily initiate an emergency shutdown) if any deviations from the fueling protocol arise:

1. T_{Amb} is less than -40°C or greater than 50°C;
2. The MOP is greater than 125% NWP;
3. P_0 is lower than 0.5 MPa or greater than the NWP;
4. Minimum gas temperature is lower than -40°C;
5. Maximum communicated CHSS gas temperature is higher than +85°C;
6. The SOC is higher than 100% (in a fault condition, it is permissible to have up to 115 % SOC only with communications);
7. Fuel flow rate is greater than 60 g/s after 30s startup (excluding main fuelling time);
8. The fuel flow rate drops below 0.6 g/s (creating a pause during fueling) more than 10 times;
9. Hydrogen mass transferred during the startup time (before actual filling) is bigger than 200 g;
10. The dispensed fuel temperature after a period of 35s (30s + 5s tolerance) from the start of the fueling, is below the minimum temperature of its category (e.g. in T40, the T_{Fuel} is < -40°C).

6) Fueling should cease when an abort or halt signal is received from the vehicle being filled (on communication fuelling).

7) Fueling should cease when the target pressure in the protocol has been achieved.

Hydrogen fueling station performance should be validated at station commissioning using a Hydrogen Station Test Apparatus (HSTA). There are FAT, factory acceptance testing, and SAT, site acceptance testing, protocols. These are tests that should be completed for all stations brought into service. There is a test to confirm that the tables are correctly programmed into the PLC through software but there are also fault simulation tests which allow testing if the fault detection and management procedures are correctly working on the refueling station.

2.2. Proposed tests to study the severity of the different out-of-spec events

In order to study the effect of the out-of-spec events described on Table 1 during actual vehicle fueling, different refueling experiments have been performed on a commercial compressed hydrogen tank. To define the refueling conditions, a non-communication fueling of a 2-4 kg category CHSS has been considered. Three different look up tables from the SAE J2601 [7] have been chosen: D19 (H70-T40 2-4 kg), D21 (H70-T20 2-4 kg) and D31 (H70-T40 7-10 kg). Combining these Tables, correct (control) and wrong (out-of-spec) refueling specifications (APRR and P_F) have been extracted combining correct and wrong inputs of CHSS capacity, ambient temperature (T_{Amb}), fuel temperature (T_{Fuel}) and initial pressure (P_0). Most of the tests have been defined for a T40 fuel temperature category, an initial pressure inside the tank of 5 MPa and an ambient temperature of 20°C. In order to find worst case scenarios for over-filling or over-heating the tank, ambient temperatures of -40°C and 50°C respectively have been considered.

3. EXPERIMENTAL

3.1 Experimental facility

The refueling experiments have been performed at the JRC's compressed hydrogen gas tanks testing facility GasTeF [15]-[18]. The facility consists of a half-buried bunker, a gas storage area and a liquefied nitrogen storage vessel. The nitrogen is used for the inertization of the facility, for the cooling of the hydrogen and for conditioning the temperature of the test chamber. GasTeF contains all the equipment and safety elements for the proper execution of pneumatic tests under hydrogen for type approval of tanks (fatigue and permeation tests) [4], [16] and for refueling experiments of on-board tanks [13], [17], [18]. The test tanks are placed inside a chamber (sleeve) placed inside a safety pressure vessel. The tanks are filled in two stages. In the first stage, the tanks are filled directly from the hydrogen bottles. In this stage, the filling speed is controlled through the opening of a valve. Once the equilibrium between gas bottles (at a pressure of 20 MPa to 24 MPa) and the tank pressure is reached, a compressor pumps the hydrogen to the tank until the pressure in the tank reaches the targeted value. This sometimes creates a nonlinear pressure profile (as it can be for example observed in Figure 4(b)). The sleeve can be heated to a temperature above 50°C (up to 85°C) [18] and with a liquid nitrogen heat exchanger, cooled down to a temperature below -40 °C. The hydrogen can be also pre-cooled at different temperatures before being introduced in the facility [17]. In this way, tests can be performed at all possible ranges of ambient and fuel temperatures considered in the SAE J2601 standard [7].

3.2 Test tank and instrumentation

The experiments have been performed on a 70 MPa NWP and 40 L inner volume (1.6 kg capacity) type 3 tank. The tank has aluminum liner and bosses and is fully wrapped with a carbon fibre/ epoxy resin composite. As in previous tests [4], [18], the tank has been instrumented with temperature sensors attached to the external wall and with a thermocouple tree measuring the temperature of the gas at different positions inside the tank. In Figure 2, a scheme of the instrumentation of the test tank shows the temperature measurement points at the external wall of the tank (TC_{TOP_FRONT}, TC_{TOP_CENTRE}, TC_{TOP_REAR}, TC_{BOTTOM_FRONT}, TC_{BOTTOM_CENTRE}, TC_{BOTTOM_REAR}) and at different points inside the tank (1 to 6). The hydrogen has been injected in the tank by a 3 mm opening injector [13].

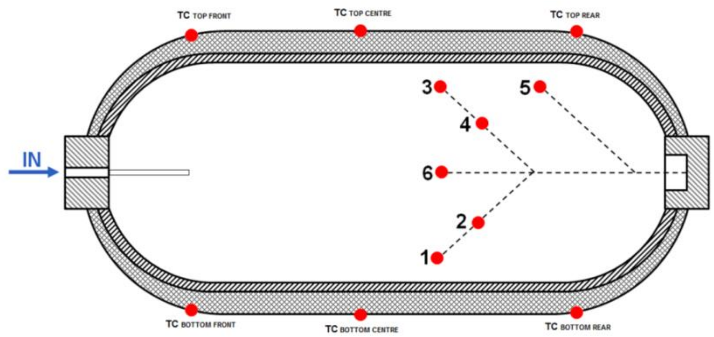

Figure 2. Axial position of the test tank with the instrumentation used for the testing.

The tank pressure has been controlled with a pressure transducer placed right in front of the tank. On the same gas line, a Coriolis mass flow meter has been placed to measure the hydrogen mass flow rate entering the tank during the filling. To control the temperature of the fuel entering the tank, a thermocouple has been placed right before the 3 meters long hose that connects the hydrogen pre-cooling system with the 300 mm long gas line in front of the tank. This measurement simulates the breakaway temperature in a refueling station [8], [14].

As in our previous work [13], the standard equation developed by NIST [19] has been used for the determination of the hydrogen gas densities. The gas density inside the tank has been calculated making use of the average gas temperature (average of sensors 1, 2, 3, 4 and 6). Recorded data of gas temperature and pressure, with a time interval of 1 second, has been used as input in the NIST equation. With the density of the gas inside the tank, the SOC has been monitored along the filling.

4. RESULTS

Table 2 lists the results of the single out-of-spec events and Table 3 the results of the combined events. In the SAE J2601 look up tables, the higher the ambient temperature the lower is the APRR and the higher is the P_F. This strategy allows balancing the heating of the gas inside the tank (which is higher the faster the filling) and the SOC (which for a constant end pressure is lower the higher the final temperature inside the tank). For each of the cases studied, the control tests (performed taking correct values of P_F and APRR from correct look up tables) have been compared with the out-of-spec test results (performed taking wrong values of P_F and APRR from the correct look up tables or choosing wrong look up tables). The monitored parameters during the tests and the deviations from the targeted values have been the following:

1. P_0 (± 1.2 MPa) is the lowest measured pressure at the beginning of the filling.
2. T_0 (± 5 °C) is the average gas temperature inside the tank at P_0. At the beginning of the test, the tank wall temperatures and the gas temperatures inside the tank (see Figure 2) are within a maximum of ± 3°C with each other.
3. P_F (± 1.5 MPa) is the maximum pressure measured at the end of the filling.
4. APRR (± 4 MPa/min) is the average pressurization rate of the filling calculated as the difference between P_F and P_0 and divided by the filling time.
5. T_{FuelAv} ± 4 °C is the temperature of the gas entering the tank (measured at the simulated break away) averaged along the filling (from P_0 to P_F) [18].

Table 2. Summary of single out-of-spec scenario results.

	Single out-of-spec scenarios	Test Type	Used Table	Test conditions						
				P_0 (MPa)	T_0 (°C)	T_{Fuel} (°C)	APRR (MPa/min)	P_{Final} (MPa)	T_{Final} (°C)	SOC (%)
Wrong selection of the CHSS capacity	1. 2-4 kg tank filled with 7-10 kg target	Control	D19	5.5	47.0	-37.1	3.4	77.4	73.0	94.2
		Out-of-spec	D31	5.5	47.1	-35.4	7.7	79.1	72.5	95.8
Wrong selection of pre-cooling category	2. T20 with T40 target @ T_{Amb} = 20 °C	Control	D21	5.6	18.9	-19.3	7.3	74.2	57.2	94.6
		Out-of-spec	D19	4.2	23.2	-20.4	20.8	75.1	63.6	94.0
	3. T20 with T40 target @ T_{Amb} = 50 °C	Control	D21	5.6	53.3	-17.8	2.6	77.8	79.8	93.3
		Out-of-spec	D19	5.5	47.9	-19.3	3.3	77.4	76.7	93.5
	4. T40 with T20 target @ T_{Amb} = 20 °C	Control	D19	5.4	19.4	-37.6	16.9	73.8	54.3	94.8
		Out-of-spec	D21	5.5	17.3	-36.2	7.3	74.7	50.2	96.4
	5. T40 with T20 target @ T_{Amb} = -40 °C	Control	D19	3.8	-39.4	-35.7	26.5	70.9	24.4	98.6
		Out-of-spec	D21	4.0	-38.9	-37.1	21.6	70.0	22.7	98.2
Failure of the cooling system	6. No cooling with T40 target @ T_{Amb} = 20 °C	Out-of-spec	D19	5.5	21.5	23.0	18.1	74.1	80.0	90.0
	7. No cooling with T40 target @ T_{Amb} = 50 °C	Out-of-spec	D19	5.4	47.1	22.6	3.2	77.2	**84.9**	91.8
	8. Cooling below -40°C with T20 target @ T_{Amb} of 20 °C	Out-of-spec	D21	5.5	21.9	-55.1	8.0	73.8	47.5	96.3
	9. Cooling below -40°C with T20 target @ T_{Amb} of -40 °C	Out-of-spec	D21	4.4	-38.0	-54.0	22.4	71.6	15.2	**101.5**
Wrong selection of Ambient Temperature	10. T_{Amb} of 50°C with -40°C target	Control	D19	5.5	47.0	-37.1	3.4	77.4	73.0	94.2
		Out-of-spec	D19	6.0	52.3	-33.9	26.9	70.2	73.6	87.8
	11. T_{Amb} of -40°C with 50°C target	Control	D19	3.8	-39.4	-35.7	26.5	70.9	24.4	98.6
		Out-of-spec	D19	4.5	-37.3	-35.6	3.5	76.9	12.6	**107.1**
	12. T_{Amb} of 20°C with 10°C target (10°C deviation on the reading)	Control	D19	4.8	22.5	-34.7	20.1	75.2	56.6	95.5
		Out-of-spec	D19	5.4	18.9	-32.4	26.7	73.8	56.1	94.4
	13. T_{Amb} of 20°C with 30°C target (10°C deviation on the reading)	Control	D19	4.8	22.5	-34.7	20.1	75.2	56.6	95.5
		Out-of-spec	D19	5.4	18.2	-36.4	12.1	75.4	52.2	96.6
Wrong selection of Initial pressure	14. P_0 of 30 MPa with target of 0.5 MPa @ T_{Amb} of -30 °C	Control	D19	28.7	-37.2	-38.2	23.9	64.1	-5.5	**99.2**
		Out-of-spec	D19	28.7	-37.2	-37.6	24.0	70.7	-2.3	**105.1**

Table 3. Summary of combined out-of-spec scenario results.

	Combined out-of-spec scenarios	Test Type	Used Table	Test conditions						
				P_0 (MPa)	T_0 (°C)	T_{Fuel} (°C)	APRR (MPa/min)	P_{Final} (MPa)	T_{Final} (°C)	SOC (%)
Wrong selection of the CHSS capacity & pre-cooling category	15. 2-4 kg tank with 7-10 kg target & T40 target on T20 station @ T_{Amb} = 20°C	Control	D21	5.6	18.9	-19.3	7.3	74.2	57.2	94.6
		Out-of-spec	D31	6.2	23.6	-21.4	19.3	76.5	62.6	95.5
	16. 2-4 kg tank with 7-10 kg target & T40 target on T20 station @ T_{Amb} = 50°C	Control	D21	5.6	53.3	-17.8	2.6	77.8	79.8	93.3
		Out-of-spec	D31	5.5	47.4	-19.4	7.1	79.2	76.7	95.0
Wrong selection of the CHSS capacity & Ambient temperature	17. 2-4 kg tank with 7-10 kg target & T_{Amb} of 50°C with 40°C target	Control	D19	5.5	47.0	-37.1	3.4	77.4	73.0	94.2
		Out-of-spec	D31	5.5	47.7	-33.0	14.0	79.0	72.8	95.6
	18. 2-4 kg tank with 7-10 kg target & T_{Amb} of 50°C with -40°C target	Control	D19	5.5	47.0	-37.1	3.4	77.4	73.0	94.2
		Out-of-spec	D31	5.5	47	-33.4	18.6	69.4	71.2	87.6
Wrong selection of the pre-cooling category & Ambient temperature	19. T40 target on a T20 station & T_{Amb} of 20°C with 10°C target	Control	D21	5.6	18.9	-19.3	7.3	74.2	57.2	94.6
		Out-of-spec	D19	4.7	23.9	-20.4	26.6	74.2	64.8	93.1
	20. T40 target on a T20 station & T_{Amb} of 50°C with -40°C target	Control	D21	5.6	53.3	-17.8	2.6	77.8	79.8	93.3
		Out-of-spec	D19	5.5	47.7	-19.0	27.9	70.1	77.6	87.0
	21. T20 target on a T40 station & T_{Amb} of 20°C with 30°C target)	Control	D19	4.8	22.5	-34.7	20.1	75.2	56.6	95.5
		Out-of-spec	D21	5.2	19.0	-36.7	4.9	75.4	49.7	97.2
	22. T20 target on a T40 station & T_{Amb} of -40°C with 50°C target	Control	D19	3.8	-39.4	-35.7	26.5	70.9	24.4	98.6
		Out-of-spec	D21	3.9	-41.7	-36.3	2.4	78.0	12.4	**108.1**
Failure of the cooling system & Wrong selection of Ambient temperature	23. T40 target but no cooling & T_{Amb} of 50°C with -40°C target	Out-of-spec	D19	5.5	47.5	25.4	29.0	70.3	**98.1**	83.6
	24. T20 target but -60°C & T_{Amb} of -40°C with 50°C target	Out-of-spec	D21	5.4	-41.1	-57.0	2.4	77.8	6.3	**109.5**

4.1. Control tests

In Figure 3, the control fillings of the D19 (H70-T40 2-4 kg) look up table for a constant P_0 of 5 MPa for two different initial temperatures are shown. As it can be observed in the figure, when starting at very low temperatures (-40°C), even if the filling is fast (< 3 minutes), the final temperature reached at the end of the filling is low (< 20°C) which results in a SOC very close to 100%. On the contrary, when starting at high ambient temperature (50°C), the filling is done slowly (> 20 min), however, it seems that in this case, the slow APRR is conservative for a type 3 tank as the gas temperature reached is 73°C, well below the allowed 85°C.

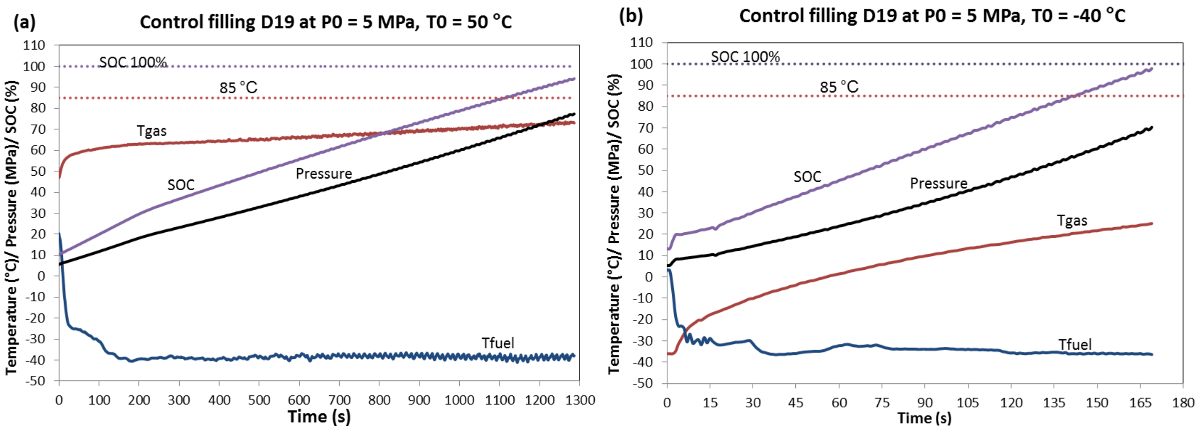

Figure 3. Fueling of a type 3 and 40 L hydrogen tank with a SAE J2601:2016 [7] D19 (H70-T40 2-4 kg) look up table for a P_0 of 5 MPa and (a) with a T_0 of 50°C (a) and (b) with a T_0 of -40°C.

On the other hand, in the SAE J2601 look up tables, the higher the initial pressure, the lower is the P_F while the APRR remains constant. The lower heating of the gas inside the tank (the higher the initial pressure) is compensated by a lower final pressure to reach a SOC close to the 100%. This can be observed in the control test of case 14 (see Table 2) where starting from an initial pressure of 30 MPa, with a final pressure of 64.1 MPa, a SOC close to 100% is reached at the end of the filling.

Note that as expected in the SAE J2601:2016 [7], in the control fillings the temperature did not surpass the safety limits of 85°C, nor did the SOC exceed 100% (SOC laid in values between 93% and 99%).

4.2. Single out-of-spec events

Looking at the different scenarios on Table 2, a wrong selection of CHSS capacity (Number 1), a wrong pre-cooling category (Numbers 2 to 5) or a deviation of the temperature sensor of ± 10°C (Numbers 12 and 13) does not seem to have negative consequences on the safety of the filling. In none of the cases was the 85°C temperature limit surpassed for the studied type 3 tank.

However, simulating a failure of the cooling system (the pre-cooling system does not cool down the gas) and at a very high ambient temperature (Number 7), the gas inside the tank reached the 84.9°C. On the other hand, for cold ambient temperature and the pre-cooling system cooling down below -40°C (Number 9), a SOC close to the 100% limit established by the SAE J2601:2016 [7] was reached. A wrong selection of the ambient temperature (targeting a higher temperature than the actual one) was the worst case scenario (Number 11). In this case, a SOC 107.1% was reached. A wrong selection of the initial pressure at a low ambient temperature (Number 14) also results in overfilling when the targeted initial pressure is lower than the actual one. In Figure 4, the temperature and pressure profiles measured during two of the tests (Nr.7 and Nr. 11) are shown.

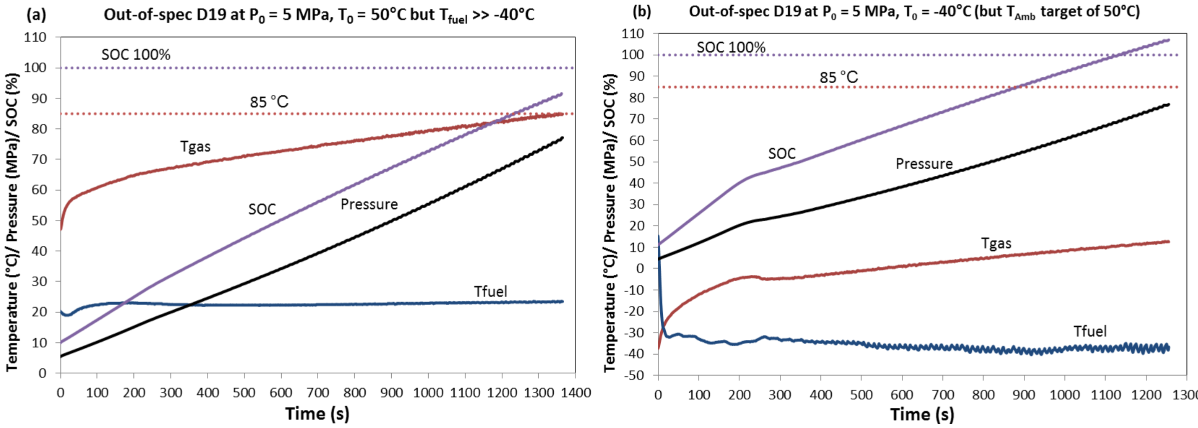

Figure 4. Refueling of a type 3 and 40 L hydrogen tank with a SAE J2601:2016 [7] for the single out-of-spec events considered on Table 2: (a) Nr. 7: the cooling system fails (T_{fuel} >> -40°C) and (b) Nr. 11: ambient temperature target is wrong (50°C target instead of -40°C).

4.3. Combined out-of-spec events

The extreme cases shown in Table 3 are combined out-of-spec events which have low probability to happen in a refueling station [8]. A wrong selection of CHSS capacity combined with a wrong selection of the pre-cooling category (Cases 15 and 16) or with a wrong selection of the ambient temperature (cases 17 and 18) does not seem to have negative consequences on the safety of the filling.

In Figure 5, the examples of combined out of specification events leading to over-temperature and over-filling respectively are shown.

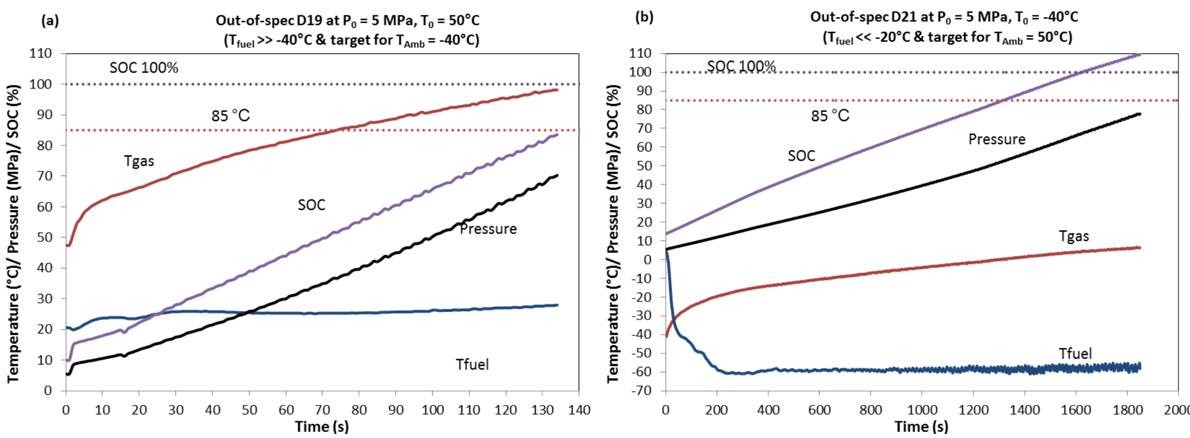

Figure 5. Refueling of a type 3 and 40 L hydrogen tank with a SAE J2601:2016 [7] for the combined out-of-spec events considered on Table 3: (a) Nr. 23: the cooling system fails (T_{fuel} >> -40°C) and ambient temperature target is wrong (-40°C instead of 50°C) and (b) Nr. 24: the cooling system fails (T_{fuel} << -20°C) and ambient temperature target is wrong (50°C instead of -40°C).

The 85°C temperature limit was only surpassed in one case (Number 23): an unnoticed failure of the cooling system (a T40 station stops cooling down the fuel) and a wrong input of ambient temperature in the look up tables (-40°C target instead of 50°C) resulted in a gas temperature of 98.1°C inside the tank (the 85°C threshold was surpassed by 13°C). For the same combined out-of-spec scenario on the type 4 tank, the 85°C threshold was exceeded by over 30°C [11].

On the other hand, on the studied type 3 tank, the 100% SOC was surpassed in two cases (Number 22 and Number 24). The warmer selection of the current ambient temperature (50°C target instead of -40°C) was combined with a fault on the delivered gas temperature. The settings were in both cases for a T20 station but in one case, the gas was delivered at -40°C (case Number 22) whereas in the other, the cooling system failed and the average gas temperature at the breakaway went down to almost -60°C (case Number 24). In this last case, a SOC of 110% was reached at the end of the filling.

5. CONCLUSIONS

For safety reasons, regulations and standards for the type approval of hydrogen powered vehicles have established gas temperature (in a range between -40°C and +85°C) and pressure (125% the nominal working pressure) limits within the compressed hydrogen storage system. To perform the refueling in a safe way, refueling protocols for light duty vehicles, like those compiled in the SAE J2601:2016, have been developed. The refueling is done in a reasonable time, reaching a state of charge close to 100% but without surpassing it.

The ISO/TS 19880-1 describes technical specifications that the gaseous hydrogen fueling stations should fulfil. It recommends the minimum design characteristics for safety and performance of fuelling stations that dispense gaseous hydrogen to light duty land vehicles. The hydrogen stations should include measures to reduce harms (from different identified hazards) and perform hydrogen refuelings in a safe way. However, during the refueling process, certain out of specification events could result in the hydrogen storage safety boundaries being surpassed.

Refuelling tests have been performed on a commercial type 3 tank using the look up tables of the SAEJ2601 for a non-communication fuelling.

It has been found that a wrong selection of compressed hydrogen storage system capacity, a wrong pre-cooling category or a deviation of ± 10°C from the real ambient temperature does not seem to have negative consequences on the safety of the filling.

Under low environmental conditions and under certain events over-filling of the type 3 tank occurred. These events include a failure of the cooling system (cooling the fuel below -40°C), an extreme wrong selection of the ambient temperature or a wrong reading of the initial pressure (the station thinks the storage system is under a lower pressure than the actual one). However, in no case the state of charge surpassed the 110%.

The maximum allowable temperature of 85°C was only surpassed under a combination of out-of-spec events (which have lower probability to happen in a refueling station). An unnoticed stop of the cooling of the gas combined with a wrong input of ambient temperature at a very warm environment, resulted in surpassing the temperature threshold by 13°C. Under the same conditions, this threshold was far exceeded in previously performed tests on a comparable type 4 tank.

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