D4.1 – Report on the experimental filling test campaign

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EXECUTIVE SUMMARY

In order to validate models and to have experimental campaign for the project HyTransfer, a test campaign was prepared. A set of parameters were identified through preliminary simulations and market analysis, after that a test matrix was prepared, with the main specificities presented here:

- 3 different test facilities industrial and scientific were used to perform the tests
- 3 different tanks were tested, including large and short tanks as well as Type III and Type IV
- For each tank a unique set of 30 thermocouples installed between the liner and the composite wrapping was installed
- In addition, tests were performed with thermocouple trees, measuring temperatures at different positions in the vertical plan
- A set of different injection diameter were installed in the tanks to study the impact of injection speed
- A variety of other parameters, focusing on the amount of energy brought in the tank were tested

In total about 80 tests were performed in the different test centers, about half fuellings and half defuellings. The first experimental observation, already allow to draw some conclusions, including:

- The inlet velocity, conditioned by the fuelling flowrate and the injection diameter, influences the creation or not of a temperature stratification during fuellings
- For defuellings which are on a longer time always create temperature stratification
- The instrumentation allowed to observe the temperature gradient between the gas and wall different temperatures, especially strong on fast fuellings
- Strategy for fuelling and defuelling efficiently within temperature limits of the tanks could be tested

This experimental campaign tested a variety of instrumented components and parameters, coordinating different test facilities. A further experimental study to identify the experimental differences depending on the test implementation would be of interest.

Numerical simulations have been conducted in link with the experiments, that could confirm most of the conclusions. A second step of experiments later in the project was to test fuelling strategies on a vehicle like test bench within Work Package 5.

1 INTRODUCTION

HyTransfer project aims at optimizing filling and defuelling processes under temperature constraints that are to stay in the range [-40°C; +85°C] inside the tank materials.

In order to have a solid scientific background, the project is constructed with a simulation Work Package (WP3) and an experimental Work Package (WP4). The project was built was to define a common basis on parameters to be studied on the simulation and the experimental part. Preliminary simulations have been conducted to identify the most relevant parameters. The test bench set up was then implemented and a set of five experiments batches has been performed. Out of the experimental results and based on the real parameters and values, a selection of CFD simulations has been performed. Simple model simulations for comparison have been performed for almost all experiments.

We present in this document the different steps, results and conclusions of the experimental work. The experimental results are presented with different objectives; the first one is to introduce the context and the different test facilities and configurations. The overall conditions, test capabilities and environment surrounding help to understand the experimental possibilities and limits. A second goal is to present with as much detail as possible the results and experimental conditions of each test. This is a key element in an experimental report, showing every little deviations and adjusted parameters that may explain the discrepancy with model results. It would thus allow either to reproduce the experiments with a good accuracy or to read and understand the results with enough information. Finally this experimental report aims at analyzing the results from an experimental perspective and drawing the first conclusions, to be later confirmed or disproved through the confrontation with simulation.

In section 2 we first introduce the parameters that have been defined in WP2 and WP3 and a short reminder of the reasons why there were chosen. This parameters have been bounded by the equipment manufacturing capacities from cylinders, instrumentation and other components, the testing capacity of each laboratory in terms of flow rate, ambient temperature and safety constraints and finally the technico-economic analysis of current industry practices and state of the art, like cylinders orientation, material characteristics.

Focusing on the experimental aspects, section 3 presents an overview of the test facilities involved in the project, showing their testing capabilities and defined scope

Having this overall vision of the experiments, it is possible to shift to the experimental reports of each laboratory in section 4, 5 and 6. Each test facility is presenting how the tests were performed. This includes the different batches, 1 short type III and 1 short type IV cylinder test serie at the Joint Reseach Center of the European Commission in Petten (NL), 1 short type III cylinder experiment subcontracted at Energie Technologie in Ottobrunn (DE) as well as 1 short type IV cylinder and 1 long type IV cylinder filling at Air Liquide advanced Technologies in Sassenage (FR).

To sum up these different results a crossed comparison of the different lab results is done in section 6 and conclusions on the experimental results as well as technical recommendations are given.

2 EXPERIMENTAL PARAMETERS

We list here the parameters defined in WP3 and used for experiments with a short explanation on the choices made. In the next section we will compare these parameters and the test facilities capacities.

2.1 Tank type :

The choice of the cylinders material and construction is based on the currently used type of cylinders. The different types of cylinders used in the industry are :

- Type I : fully metallic cylinders – most widespread technology
- Type II : metallic cylinders with a composite wrapping reinforcement – improvement in weight of the previous cylinders
- Type III : metallic liner cylinder with a composite wrapping – mainly composite cylinder and first used technology for hydrogen mobility
- Type IV : polymer liner cylinder with a composite wrapping – mainly composite cylinder and foreseen as hydrogen mobility main technology

The project aims at evaluating the temperature behaviour of hydrogen during fuelling and defuelling. The thermal behaviour in Type I and Type II are limited compared to the composite cylinders and already well understood. The temperature behaviours have a significant impact on Type III and Type IV, widely used in mobile applications. The cylinders chosen for the experimental work are thus Type III and Type IV. Hexagon Lincoln (HEX), member of the consortium, produces only Type IV and provided them for the experimentations, while the Type III cylinders were supplied by Dynetek Luxfer (DYN), one of the most experienced manufacturers in Type III cylinders.

Before being delivered to the laboratories, the cylinders have been pressure tested to identify the impact of the thermocouples inserted between liner and composite wrapping. Hexagon Lincoln performed one burst test and two burst tests after 5000 pressure cycle test at nominal working pressure for each cylinder type. For the Dynetek cylinder, similar tests were performed at the CTE testing centre of Air Liquide. These tests helped to allow the testing of cylinders in France and have shown no noticeable impact of the inserted thermocouples on the tank characteristics.

2.2 Tank size :

The tank size choice is defined by the application and the L/D ratio, where L is the internal length of the cylinder and D its internal diameter.

Looking at the application, first in vehicles applications, the mainly used cylinders are short cylinders with an L/D < 3, for space availability reasons. Less frequently the L/D exceeds 3. Secondly the trailer for hydrogen supply application is focusing on long cylinders for capacity maximisation and L/D > 3 when installed horizontally on trailers. Some configurations may have an L/D < 3.

Based on preliminary simulations two different flow regimes depending on L/D have been identified. At the beginning of the project the L/D limit wasn't clearly identify but the target was to test two L/D , one below 3 and one really above 3. (L/D exceeding 8 are barely found).

Following this considerations and the tank available for supply, two cylinders of 36L and an L/D = 2.4 were supplied by Hexagon Lincoln (called HEX36), one cylinder of 531L and an L/D = 5.6 was supplied by Hexagon Lincoln (called HEX531) and one cylinder of 40L and an L/D = 2.7 was supplied by Dynetek Luxfer (called DYN40). Most of cylinders tested are short with an L/D < 3 because the focus is on vehicles applications and also to comply with size restrictions in test laboratories.

On Figure 1, we present the pictures of the 3 chosen tanks.

Figure 1: From left to right, HEX36, HEX531 and DYN40 cylinders.

2.3 Tank orientation :

The absolute majority of tanks, especially in vehicles applications are placed horizontally. Adding the difficulty to easily install the tanks horizontally in the test facilities all experiments were conducted with horizontal position.

The good understanding of fluid mechanics behaviours in the tank in the project would allow evaluating the behaviour in vertical tanks, with some additional studies. This parameter is applicable for both fuelling and defuelling experiments.

2.4 Injection diameter :

Associated with the L/D ratio, there is a second ratio influencing the thermal behaviour on the tank, it is d_{inj}/D where d_{inj} is the injection diameter in the tank and D the internal diameter of the tank. This parameter defines the injection speed in the tank for a given flow. In an experimental perspective, we have designed and produced injectors with diameters of 3 mm, 6 mm and 4 x 3 mm (called radial) that were placed in the inlet of the tanks. A last diameter was without placing any injector, leaving the inlet fitting 10 mm diameter as an injection diameter.

Table 1 summarize the different injection sizes and Figure 2 shows different injectors.

Table 1 : Summary of injection diameters configurations

Configuration	Diameter	Injector	Orientation	Length in the tank (L_{inj})
1	3 mm	Yes	Axial	100 mm
2	6 mm	Yes	Axial	100 mm
3	10 mm	No	Axial	0 mm
4	4x 3 mm	Yes	Radial	100 mm

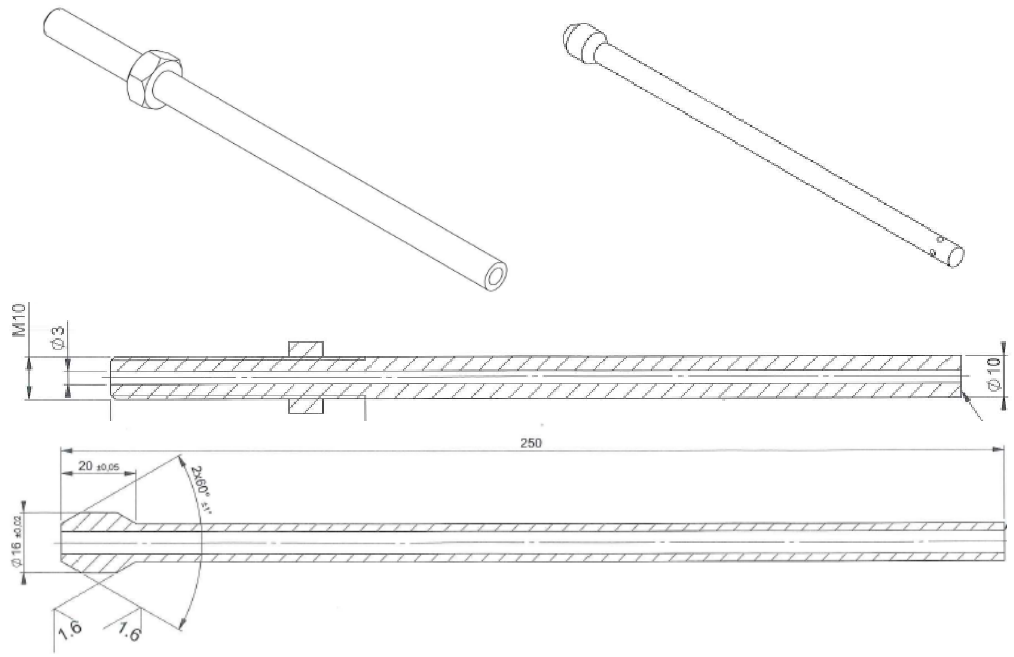


Figure 2 : Different views and diameters of small and large tank injectors

This parameter is applicable for both fuelling and defuelling experiments.

2.5 Initial tank gas and wall temperature :

This parameter represents the ambient conditions around the tank. The standard range of temperatures, defined in SAE J2601 for example is from -40°C to 50°C, with an average around 20°C. The idea is to test the cylinders in a temperature range wide enough to evaluate the impact of this parameter, rather than having an exact representation of ambient temperatures in different geographies.

According to the facilities capacities, it was chosen to perform tests at -40°C, -20°C, 20°C and 50°C, as well as no conditioning. This parameter is applicable for both fuelling and defuelling experiments. Fuelling [-40°C; -20°C, 20°C, 40°C + no conditioning] and Defuelling [-20°C, 20°C, 50°C + no conditioning].

2.6 Initial pressure condition :

2.6.1 Fuelling – Initial pressure

This parameter gives the initial condition before fuelling the tank. The different pressures are given at 15°C standard reference temperature. Practically during the experiments the pressure was set at the value, almost neglecting the temperature effect.

It was already well known that the initial pressure when increased diminished the temperature elevation in the tank. Additionally a low pressure allows a longer development of the thermal effect. The values chosen are thus :

- 5 bar represents the lowest acceptable pressure in a vehicle, still allowing to detect a leak. This is the most conservative case.
- 20 bar is a conservative case closer to the reality of an empty vehicle. For a trailer, this is a representative refilling condition, as application can consume hydrogen down to 10 – 30 bar.
- 100 bar is a value of a partially empty tank either for a vehicle or a trailer and was chosen to clearly identify the impact of an higher initial pressure.

2.6.2 Defuelling – Initial State Of Charge (*SOC*)

The State Of Charge - SOC is defined as the actual density over the target density, this means for the application we are looking at the target pressure at 15°C, for example 700 bar, 15°C ρ = 40,2 kg/m^3

When looking at defuelling, we mainly want to have a look at vehicle completely or a trailer newly delivered, this way the initial SOC are :

- 100% for most of the defuellings as the most conservative case
- 80% to evaluate the impact of a lower initial condition

2.7 Final pressure condition :

2.7.1 Fuelling – Final State Of Charge (*SOC*)

The SOC was defined previously. In a vehicle or a trailer the target of fuelling is the stored mass, which is the only comparable value between different fuellings, as long as the maximum pressure and temperature of the system are respected.

To have the best overview of the thermal effects, all the fuellings are performed up to 100% SOC, with respect to other safety limits (Tmax = 85°C and Maximum Working Pressure of the cylinder. An easy way to evaluate approximately the conditions for a lower SOC is to extract the data at the appropriate time.

Nota : There is an exception for four fuellings, where the target is to evaluate the impact of pre-cooling the hydrogen for a given temperature and time then reduce the cooling for the same given time compared to a reduced pre-cooling for the same given time followed by the same given time and temperature pre-cooling

2.7.2 Defuelling – Final pressure

For the defuelling the target is to stop with a pressure as long as the minimum temperature is respected. The optimized use of the hydrogen while avoiding liner collapse or buckling issues is to go down to 20 bar. All the final pressure conditions are given here, with respect to the safety limits (Tmin = -40°C) :

- 5 bar is an extreme case that is performed at reduced flowrate and represents the defuelling of a vehicle, trailer or system before maintenance
- 20 bar is the optimized target pressure and reference pressure
- 200 bar is taken for a high flow defuelling scenario, where going below this value at such a flow rate could damage the cylinder

2.8 Mass flow rate :

2.8.1 Fuelling

For fuelling the objective is to take one low flow and one high flow, representing different situations. Two flow rates are tested in these experiments:

- 2 g/s: this is taken to represent the filling of one tank of 15 kg (based on available long cylinders) in a tube trailer in about 2 hours. For a vehicle it would represent a long fill of about 10 to 15 minutes. This parameter will highlight the low flow thermal behaviours.

- 8 g/s: this represents the fast filling of one tank of 1,5 kg (based on available short cylinders) in a vehicle in about 3 minutes. For a trailer or a fixed storage this would be a fast filling in 30 minutes. This parameter will highlight the high flow thermal behaviours.

2.8.2 Defuelling

For the defuelling the values are representing different scenarios and are adapted for each tank:

- 0,125 g/s for short tanks represents a defuelling in about 3 hours.
- 0,188 g/s for short tanks represents a defuelling in about 2 hours.
- 0,376 g/s for short tanks represents a defuelling in about 1 hour, this would be a fast driving on a highway.
- 2 g/s for short tanks is an extreme case defuelling in 10 to 15 minutes. This will show the thermal behaviours in highly constrained conditions.

- 1 g/s for long tanks represents the defuelling of a trailer in about 4 hours or the use of a fixed storage for refuelling other storages.
- 2 g/s for long tanks represents the defuelling of a trailer in about 2 hours, which represents a standard cascade between a trailer and a fixed storage.
- 8 g/s for long tanks represents a quick defuelling in 30 minutes of a trailer, this can be an optimized cascade from a trailer and a fixed storage.
- 15 g/s for long tanks represent an extreme case (trailer empty in 15 minutes) coupled with a slower flow rate, which could also represent the use of a fixed storage during balancing with a vehicle. This will show the thermal behaviours during fast defuelling.

Nota: Some of the defuellings especially for long tanks and fast defuellings are a combination of high flow rate and low flow rate. This was explored to define an optimized defuelling strategy.

2.9 Gas pre-cooling temperature – Fuelling only :

This temperature is taken as closed as possible to the inlet of the tank, to represent the gas temperature before it is impacted by the tank configuration. This is only applicable for fuelling experiments. Based on standard protocols like SAE J2601, following temperatures were chosen:

- -40°C is the extreme limit of current protocols and used especially for high flow rates. This value defines one pre-cooling boundary.

- -20°C is the average pre-cooling temperature, chosen regarding two aspects. First the goal of the protocol is to optimize the cooling need, thus a reduced pre-cooling temperature should not prevent to fulfil the fuelling. Secondly, the set pre-cooling temperature is for the dispenser in a refuelling station. The gas will then flow through the hose and the vehicle tubes and be warmer right before the tank inlet.
- 0°C / no conditioning is used for slower flow rates and represents an optimization of the pre-cooling up to ambient pre-cooling. This can be seen as another pre-cooling boundary (no or limited pre-cooling).

The pre-cooling target needed to be reached as fast as possible within 30s. This was adapted depending on the test facility.

Nota : There is an exception for four fuellings, where the target is to evaluate the impact of pre-cooling the hydrogen for a given temperature and time then reduce the cooling for the same given time compared to a reduced pre-cooling for the same given time followed by the same given time and temperature pre-cooling. We can define it as adjusted pre-cooling.

2.10 Reference cases :

Following the definition of these parameters, a fuelling and a defuelling reference cases were defined, as the combination of the most representative real fuelling and the most useful fuelling towards simulation validation:

FUELLING REFERENCE CASE:

Position	*Injector Ø*	*Initial P*	*Initial T*	*Inlet gas T*	*Average mass flow*	*End of fill*
Horizontal	3 mm	20 bar	20°C /ambiant	-20°C	8 g/s	SOC 100% or Tgas > 85°C

DEFUELLING REFERENCE CASE:

Position	*Injector Ø*	*Initial SOC*	*Initial T*	*Average mass flow*	*End of fill*
Horizontal	3 mm	100%	20°C /ambiant	0,376 g/s (small) - 2 g/s (long)	P< 20 bar or Tgas > 85°C

After the definitions of all these parameters, a test matrix with variations of each parameter was built and affected to the different laboratories capacities. It will be presented in next section for each laboratory.

3 EXPERIMENTAL FACILITIES

In this section, we present the three experimental facilities used, with their capacities put in front of the parameters defined before. The test matrix is then presented for each facility.

3.1 European Commission – Joint Research Centre, Petten, NL :

The Joint Research Centre (JRC) of the European Commission is a research centre and test laboratory contributing to research and developments funded by the European Commission.

Regarding the testing facility, it is equipped with a bunker containing a testing chamber with compressors, pre-cooler and all the instrumentation for data recording. Figure 3 shows a schematic of the facility.

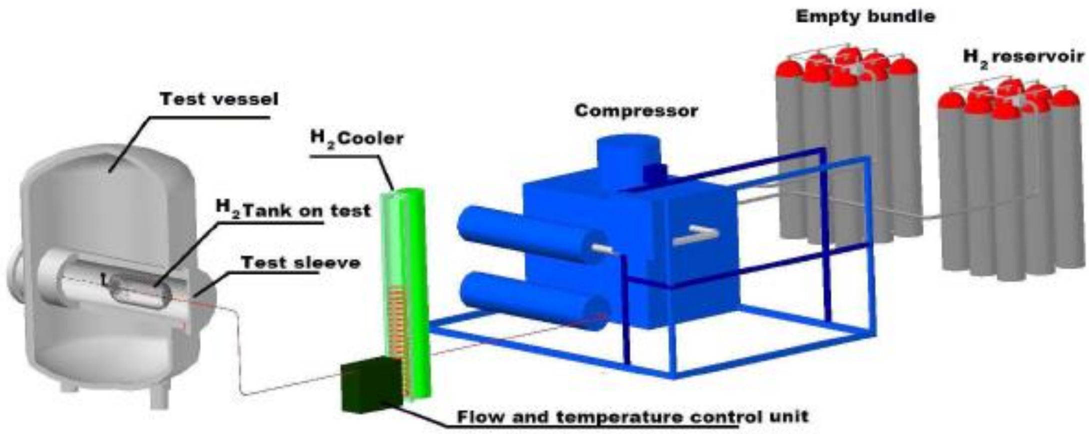


Figure 3 : JRC testing facility

We now look at the capacities of the testing facility for each parameter in Table 2 and Figure 4 :

Table 2 : JRC testing capacity evaluation

Parameter	Evaluation	Comments
Tank size	2	The tank is placed in a conditionning temperature room limited to short tanks
Initial temperature	4	Conditionning room allows the tank to be prepared between ambient and +50°C
Initial pressure	5	No restriction

Final pressure	5	No restriction
Mass flow rate	3	The flow is limited by the compressor around 12 g/s
Pre-cooling temperature	5	No limitation down to -40°C

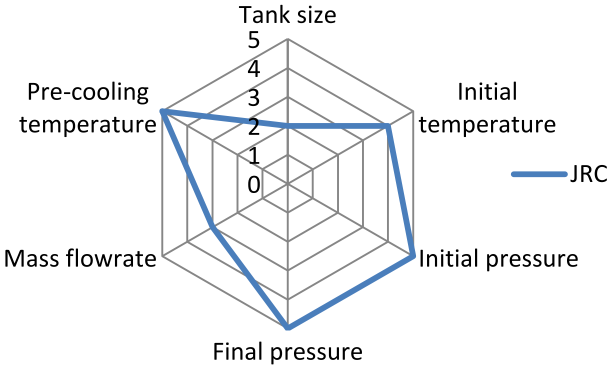


Figure 4 : JRC testing facility evaluation

In addition the JRC had already developed a thermocouple tree able to measure temperatures at various positions in a plan inside the tank, as shown in Figure 5. The JRC was also involved through its CFD simulation, with the advantage of having experimental and simulation experts working at the same location.

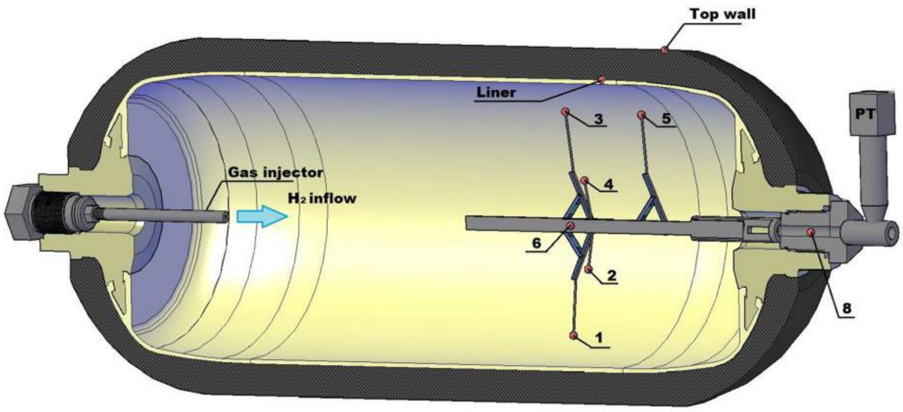


Figure 5 : JRC Thermocouple tree n° 1 to 8

The only limitation of the JRC laboratory is the capacity to receive large cylinders. The mass flow rate chosen here are within the range of the test facility. We can now present the matrix of the tests performed at JRC. We show them for each tank, as each tank was tested separately. The table are divided in experiments to validate the simple model for filling conditions, experiments to identify the conditions creating temperature disparities (beyond simple model but identified in CFD models) for filling conditions, experiments to validate an approach based on the energy inserted in the tank to evaluate the temperatures during filling and finally a set of experiments to characterize the defuelling conditions.

3.1.1 Type III tank – Dynetek 40L

Simple Model Validation – Filling: these tests are focusing on homogeneous conditions and having the other parameters varying. For this cylinder the tests were mainly conducted at ET, only the reference case was done at JRC, as shown in Table 3

Table 3: DYN40L Simple Model Validation testing at JRC

Bank_5_DYN_40L_JRC	Cyl. 3 : DYN 40 L - 700 bar	JRC	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas initial temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case	1	horizontal	3mm	20 barg	Tg1: 20°C	-20°C	8 g/s	SOC=100% or Twall>85°C

Temperature Disparities – Filling: these tests are focusing on heterogeneous conditions and having the other parameters varying. For this cylinder the tests were all conducted at ET.

Energy Based – Filling: these tests are focusing on the cooling profile. They compare different way to provide the same amount of energy in the tank. The reference case is already performed in previous series. The comparison is done between the reference case at constant pre-cooling, a fuelling with colder pre-cooling provided only on the first half of fuelling and the same fuelling with pre-cooling provided only on the second half of the fuelling, as shown in Table 4

Table 4: DYN40L Energy Based testing at JRC

Bank_5_DYN_40L_JRC	Cyl. 3 : DYN 40 L - 700 bar	JRC	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas initial temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case - constant cooling		horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Cooling during first half	2	horizontal	3mm	20 barg	20°C	Tin = 0°C for 75s then Tin = -40°C for 75s	8 g/s	time = 150s
Cooling during second half	3	horizontal	3mm	20 barg	20°C	Tin = -40°C for 75s then Tin = 0°C for 75s	8 g/s	time = 150s

Defuelling: these tests are studying the thermal behaviours during a defuelling. They follow the previous fuellings, we have the reference case, a defuelling with high ambient temperature and a defuelling with a pressure ramp change, as shown in Table 5

Table 5: DYN40L Defuelling testing at JRC

Bank_5_DYN_40L_JRC	Cyl. 3 : DYN 40 L - 700	JRC	Emptyings				
	Test number	Position of tank	Injector diameter	Initial SOC	cylinder and gas temperature	Mass flow	End of defueling criterion
Ref case	1	horizontal	3mm	100%	20°C	Constant 0.376g/s	pressure < 20 barg or Tgas<-40°C
	2	horizontal	3mm	100%	50°C	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	3	horizontal	3mm	100%	20°C	1.5g/s for 500s then 0.2g/s for the rest of the defueling	pressure < 20 barg or Tgas<-40°C

3.1.2 Type IV tank – Hexagon 36L

Simple Model Validation – Filling: these tests are focusing on homogeneous conditions and having the other parameters varying. Each parameter is modified once to see its impact on the fuelling compared to the reference case. One exception is the fuelling without cooling, that is at a reduced flow to avoid overtemperatures, as shown in Table 6

Table 6: HEX36L Simple Model Validation testing at JRC

Bank_3_HEX_36L_JRC	Cyl. 2 : HEX 36 L - 700 bar	JRC	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Cylinder and gas inital temeprature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case	1	horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Repeatability test (=Ref case)	2	horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Initial pressure change	3	horizontal	3mm	100 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Initial T° change	4	horizontal	3mm	20 barg	40°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Mass flow rate change	5	horizontal	3mm	20 barg	20°C	-20°C	2g/s	SOC=100% or Tgas>85°C
No temp control	6	horizontal	3mm	20 barg	20°C	No cooling	2g/s	SOC=100% or Tgas>85°C
Diameter change	7	horizontal	10mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C

Temperature Disparities – Filling: these tests are focusing on heterogeneous conditions and having the other parameters varying. Only some of the tests are done, as others where done in the previous table. The main variation factor here is the injection diameter and the flow rate, as shown in Table 7

Table 7: HEX36L Temperature Disparities testing at JRC

Bank_3_HEX_36L_JRC	Cyl. 2 : HEX 36 L - 700 bar	JRC	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Cylinder and gas inital temeprature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case (D1 - F1)		horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
D1 - F2		horizontal	3mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2 - F1	3	horizontal	6mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
D2 - F2	4	horizontal	6mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85°C
D3 - F1		horizontal	10mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
D3 - F2	6	horizontal	10mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2r - F2	7	horizontal	4 x 3 mm rad.	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85°C

Energy Based – Filling: these tests are focusing on the cooling profile. They compare different way to provide the same amount of energy in the tank. The reference case is already performed in previous series. The comparison is done between the reference case at constant pre-cooling, a fuelling with colder pre-cooling provided only on the first half of fuelling and the same fuelling with pre-cooling provided only on the second half of the fuelling, as shown in Table 8

Table 8: HEX36L Energy Based testing at JRC

Bank_3_HEX_36L_JRC	Cyl. 2 : HEX 36 L - 700 bar	JRC	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case - constant cooling		horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C
Cooling during first half	2	horizontal	3mm	20 barg	20°C	Tin = 0°C for 75s then Tin = -40°C for 75s	8 g/s	time = 150s
Cooling during second half	3	horizontal	3mm	20 barg	20°C	Tin = -40°C for 75s then Tin = 0°C for 75s	8 g/s	time = 150s

Defuelling: these tests are studying the thermal behaviours during a defuelling. They follow the previous fuellings, we have the reference case, a repeatability test, a defuelling with high ambient temperature, a defuelling with slower flow rate and a defuelling with faster flow rate, as shown in Table 9

Table 9: HEX36L Defuelling testing at JRC

Bank_3_HEX_36L_JRC	Cyl. 2 : HEX 36 L - 700 bar	JRC	Emptyings				
	Test number	Position of tank	Injector diameter	Initial SOC	Initial cylinder and gas temperature	Average Mass flow	End of defueling criterion
Ref case	1	horizontal	3mm	100%	No conditionning	Constant 0.376g/s	pressure < 20 barg or Tgas<-40°C
Repeatability (=ref case)	2	horizontal	3mm	100%	No conditionning	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	3	horizontal	3mm	100%	50°C	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	4	horizontal	3mm	100%	No conditionning	Constant 0.188 g/s	pressure < 20 barg or Tgas<-40°C
	5	horizontal	3mm	100%	No conditionning	Constant 2 g/s	pressure < 200 barg or Tgas<-40°C

A total of 16 fuellings and 16 defuellings (including 8 defined in table) have been performed on Type III and Type IV short tanks at the JRC test facility. The detail of the experimental campaign is given in the following sections.

3.2 Air Liquide advanced Technologies, Sassenage, FR :

Air Liquide advanced Technologies (AL-aT) is the high and new technologies development center of Air Liquide Group.

Regarding the testing facility, it is equipped with an outdoor testing area with various hydrogen fuelling infrastructures, including compressors, pre-cooler and storage. Figure 6 gives an overview of the facility.

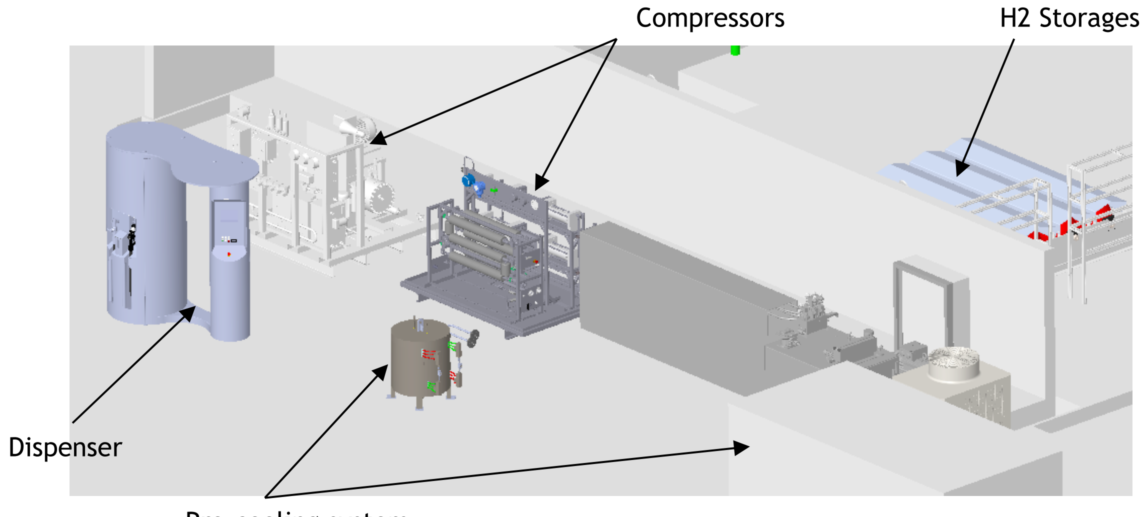


Figure 6: AL-aT testing facility

We now look at the capacities of the testing facility for each parameter in Table 10 and Figure 7 :

Table 10: AL-aT testing capacity evaluation

Parameter	Evaluation	Comments
Tank size	5	Virtually no limitation as tests are done outside in a free space
Initial temperature	1	No conditionning, ambiant temperature
Initial pressure	5	No restriction
Final pressure	4	Local regulation limits maximum pressure
Mass flow rate	4	No restriction except bank change for large tanks
Pre-cooling temperature	5	Installation not tuned for -40°C

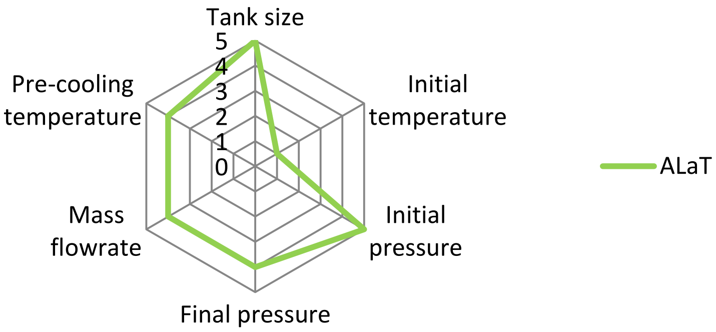


Figure 7: AL-aT testing facility evaluation

In order to measure the temperature at different points in the tanks, Air Liquide has developed and had constructed by a supplier two thermocouple trees to be inserted in the different size of cylinders as shown in Figure 8. AL-aT was also involved through its CFD simulation, with the advantage of having experimental and simulation experts working at the same location.

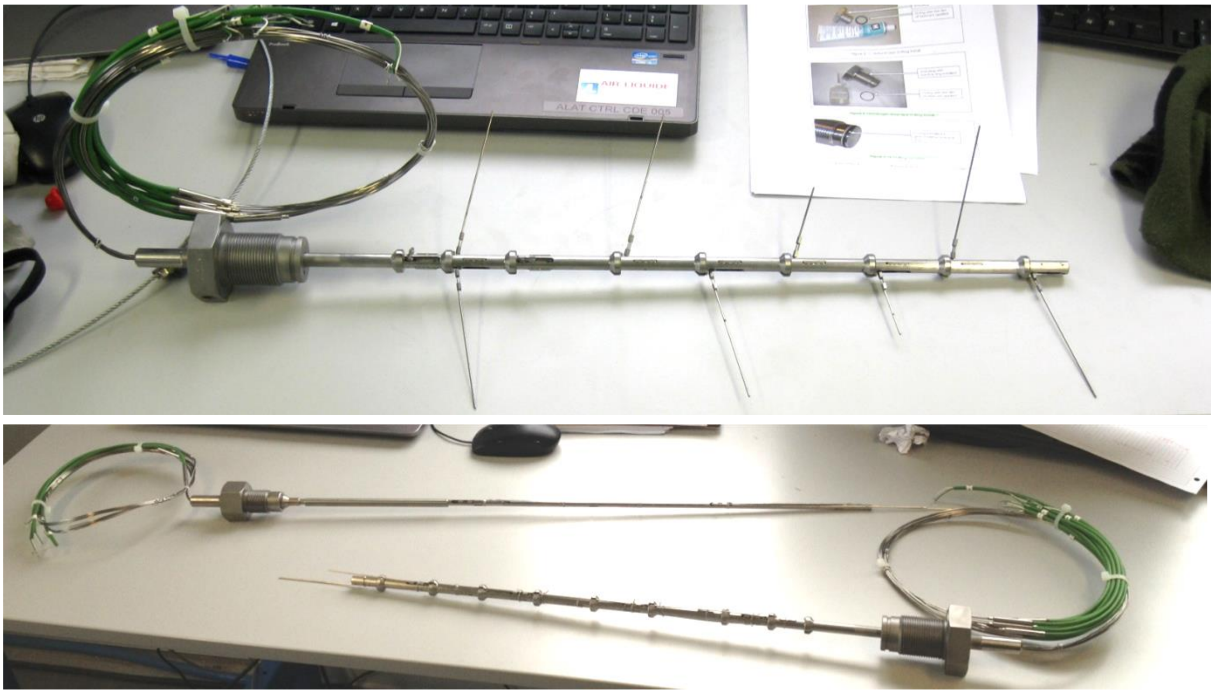


Figure 8: AL-aT Thermocouple trees

The main limitation of AL-aT test facility is to be outdoor and have no mean of controlling the ambient temperature. A parameter “no conditioning” was thus defined for AL-aT testing. Additionally local regulation imposed to stop the fuelling around 700 bar maximum for short tanks and 450 bar for large tanks. We can now present the matrix of the tests performed at AL-aT. We show them for each tank, as each tank was tested separately. The tables are divided in experiments to validate the simple model for filling conditions, experiments to identify the conditions creating temperature disparities (beyond simple model but identified in CFD models) for filling conditions and finally a set of experiments to characterize the defuelling conditions.

3.2.1 Type IV tank – Hexagon 531L

Simple Model Validation – Filling: these tests are focusing on homogeneous conditions and having the other parameters varying. Each parameter is modified once to see its impact on the fuelling compared to the reference case. One exception is the fuelling without cooling, that is at a reduced flow to avoid overtemperatures, as shown in Table 11

Table 11: HEX531L Simple Model Validation testing at AL-aT

Bank_1_HEX_531L_ALAT	Cyl. 1 : HEX 531 L - 500 bar	ALAT	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case	1	horizontal	3mm	20 barg	No conditionning	-20°C	8g/s	SOC=100% or Tgas>85°C
Repeatability test (=Ref case)	2	horizontal	3mm	20 barg	No conditionning	-20°C	8g/s	SOC=100% or Tgas>85°C
Initial pressure change	3	horizontal	3mm	100 barg	No conditionning	-20°C	8g/s	SOC=100% or Tgas>85°C
Inlet gas T° change	4	horizontal	3mm	20 barg	No conditionning	-40°C	8g/s	SOC=100% or Tgas>85°C
Mass flow rate change	5	horizontal	3mm	20 barg	No conditionning	-20°C	2g/s	SOC=100% or Tgas>85°C
No temp control	6	horizontal	3mm	20 barg	No conditionning	No cooling	2g/s	SOC=100% or Tgas>85°C
Diameter change	7	horizontal	10mm	20 barg	No conditionning	-20°C	8g/s	SOC=100% or Tgas>85°C
filling with stabilization	8	horizontal	3mm	20 barg	No conditionning	-20°C	8g/s with 3 10 minutes stop at 100 bara, 300 bara, 500 bara	SOC=100% or Tgas>85°C

Temperature Disparities – Filling: these tests are focusing on heterogeneous conditions and having the other parameters varying. Only some of the tests are done, as others where done in the previous table. The main variation factor here is the injection diameter and the flow rate, as shown in Table 12

Table 12: HEX531L Temperature Disparities testing at AL-aT

Bank_1_HEX_531L_ALAT	Cyl. 1 : HEX 531 L - 500 bar	ALAT	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case (D1 - F1)		horizontal	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D1 - F2		horizontal	3mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2 - F1	3	horizontal	6mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D2 - F2	4	horizontal	6mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D3 - F2		horizontal	10mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D3 - F1	6	horizontal	10mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2r - F2	7	horizontal	D2r: 4 x 3 mm rad.	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C

Energy Based – Filling: these tests are focusing on the cooling profile. They compare different way to provide the same amount of energy in the tank. These cases were only defined to be performed at JRC, which had the capacity to perform these tests as additional tests.

Defuelling: these tests are studying the thermal behaviours during a defuelling. They follow the previous fuellings, we have the reference case, a repeatability test, different defuellings with high flow rate followed by a lower flow rate or the opposite, a defuelling with slower flow rate and a defuelling without injector, as shown in Table 13

Table 13: HEX531L Defuelling testing at AL-aT

Bank_1_HEX_531L_ALAT	Cyl. 1 : HEX 531 L - 500 bar	ALAT	Emptyings				
	Test number	Position of tank	Injector diameter	Initial SOC	Initial cylinder and gas temperature	Mass flow	End of defueling criterion
Ref case	1	Horizontal	3mm	100%	No conditionning	Constant 2 g/s	pressure < 20 barg or Tgas<-40°C
Repeatability (=ref case)	2	horizontal	3mm	100%	No conditionning	Constant 2 g/s	pressure < 20 barg or Tgas<-40°C
	3	horizontal	3mm	100%	No conditionning	8 g/s for 1000s, then 1 g/s until end of defueling criterion	pressure < 20 barg or Tgas<-40°C
	4	horizontal	3mm	100%	No conditionning	1 g/s for 6040s, then 8 g/s until end of defueling criterion	pressure < 20 barg or Tgas<-40°C
	5	horizontal	3mm	100%	No conditionning	15 g/s for 500s then 1g/s until end of defueling criterion	pressure < 20 barg or Tgas<-40°C
	6	horizontal	3mm	100%	No conditionning	Constant 1 g/s	pressure < 20 barg or Tgas<-40°C
	7	horizontal	10mm	100%	No conditionning	Constant 2 g/s	pressure < 20 barg or Tgas<-40°C

3.2.2 Type IV tank – Hexagon 36L

Simple Model Validation – Filling: these tests are focusing on homogeneous conditions and having the other parameters varying. Each parameter is modified once to see its impact on the fuelling compared to the reference case. One exception is the fuelling without cooling, that is at a reduced flow to avoid overtemperatures, as shown in Table 14. They are same tests as at JRC but without ambient temperature conditioning.

Table 14: HEX36L Simple Model Validation testing at AL-aT

Bank_2_HEX_36L_ALAT	Cyl. 2 : HEX 36 L - 700 bar	ALAT	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case	1	horizontal	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
Repeatability test (=Ref case)	2	horizontal	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
Initial pressure change	3	horizontal	3mm	100 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
Inlet gas T° change	4	horizontal	3mm	20 barg	No conditionning	-40°C	8 g/s	SOC=100% or Tgas>85°C
Mass flow rate change	5	horizontal	3mm	20 barg	No conditionning	-20°C	2g/s	SOC=100% or Tgas>85°C
No temp control	6	horizontal	3mm	20 barg	No conditionning	No cooling	2g/s	SOC=100% or Tgas>85°C
Diameter change	7	horizontal	10mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C

Temperature Disparities – Filling: these tests are focusing on heterogeneous conditions and having the other parameters varying. Only some of the tests are done, as others where done in the previous table. The main variation factor here is the injection diameter and the flow rate, as shown in Table 15. They are same tests as at JRC but without ambient temperature conditioning.

Table 15: HEX36L Temperature Disparities testing at AL-aT

Bank_2_HEX_36L_ALAT	Cyl. 2 : HEX 36 L - 700 bar	ALAT	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case (D1 - F1)		horizontal	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D1 - F2		horizontal	3mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2 - F1	3	horizontal	6mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D2 - F2	4	horizontal	6mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D3 - F1		horizontal	10mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85°C
D3 - F2	6	horizontal	10mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C
D2r - F2	7	horizontal	D2r: 4 x 3 mm rad.	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85°C

Energy Based – Filling: these tests are focusing on the cooling profile. They compare different way to provide the same amount of energy in the tank. These cases were only defined to be performed at JRC, which had the capacity to perform these tests as additional tests.

Defuelling: these tests are studying the thermal behaviours during a defuelling. They follow the previous fuellings, we have the reference case, a repeatability test, a defuelling with a lower initial SOC, a defuelling with slower flow rate and a defuelling with faster flow rate,a defuelling with flow rate change and one without injector as shown in Table 16

Table 16: HEX36L Defuelling testing at AL-aT

Bank_2_HEX_36L_ALAT	Cyl. 2 : HEX 36 L - 700 bar	ALAT	Emptyings				
	Test number	Position of tank	Injector diameter	Initial SOC	Initial cylinder and gas temperature	Average Mass flow	End of defueling criterion
Ref case	1	horizontal	3mm	100%	No conditionning	Constant 0.376g/s	pressure < 20 barg or Tgas<-40°C
Repeatability (=ref case)	2	horizontal	3mm	100%	No conditionning	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	3	horizontal	3mm	100%	No conditionning	1.5g/s for 500s then 0.2g/s for the rest of the defueling	pressure < 20 barg or Tgas<-40°C
	4	horizontal	3mm	80%	No conditionning	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	5	horizontal	10mm	100%	No conditionning	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	6	horizontal	3mm	100%	No conditionning	Constant 0.125 g/s	pressure < 20 barg or Tgas<-40°C
	7	horizontal	3mm	100%	No conditionning	Constant 2 g/s	pressure < 200 barg or Tgas<-40°C

A total of 23 fuellings and 23 defuellings (including 14 defined in table) have been performed on Type IV short and large tanks at AL-aT test facility. Some additional high flow rate tests have been performed and are presented in following sections with the detail of the experimental campaign.

3.3 ET Energie Technologie, Brunnthal, DE :

ET is a service provider. Its main abilities related to the hydrogen technology are based on the company owned test-area with existing and flexibly adaptable hydrogen infrastructure, which can be used by the customer for his development work. The ET-Hydrogen Laboratory offers a wide variety of hydrogen test applications both cryogenic and high pressure (up to 135 MPa).

Regarding the testing facility, it is equipped with test stands underground and outside supplied by H2 compressors and a range of cylinders. Separate control rooms are used for the control and data recording. Figure 9 shows a schematic of the facility.

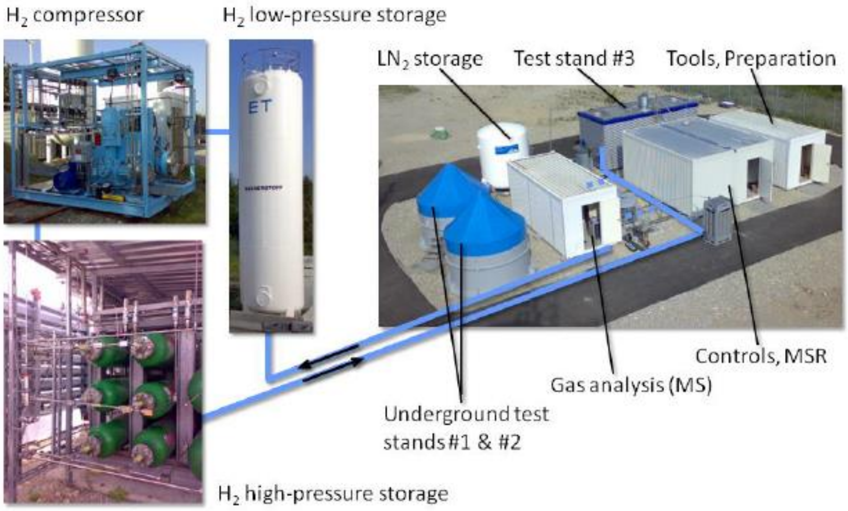


Figure 9: ET testing facility

We now look at the capacities of the testing facility for each parameter in Table 17 and Figure 10:

Table 17: ET testing capacity evaluation

Parameter	Evaluation	Comments
Tank size	3	The tank is placed in a conditionning temperature room limited to short tanks, possibility for long tanks
Initial temperature	5	Conditionning room allows the tank to be prepared between -40°C and +85°C
Initial pressure	5	No restriction
Final pressure	5	No restriction
Mass flow rate	4	No restriction except maybe the capacity for large tanks

Pre-cooling temperature	5	No limitation down to -40°C

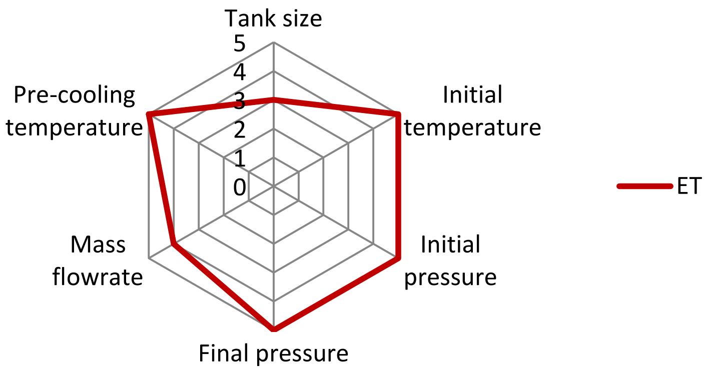


Figure 10: ET testing facility evaluation

ET worked as a testing subcontractor of the project, there only work was dedicated to experiments. The DYN40L tank tested was sent from JRC with all temperature measurements already installed.

ET has good testing capacities, but only a few tests were performed there, as the main testing were performed by the consortium partners. We can now present the matrix of the tests performed at ET. We show them for each tank, as each tank was tested separately. The table are divided in experiments to validate the simple model for filling conditions, experiments to identify the conditions creating temperature disparities (beyond simple model but identified in CFD models) for filling conditions and finally a set of experiments to characterize the defuelling conditions.

3.3.1 Type III tank – Dynetek 40L

Simple Model Validation – Filling: these tests are focusing on homogeneous conditions and having the other parameters varying. Each parameter is modified once to see its impact on the fuelling compared to the reference case. One exception is the fuelling without cooling, that is at a reduced flow to avoid overtemperatures, as shown in Table 18.

Table 18: DYN40L Simple Model Validation testing at ET

Bank_4_DYN_40L_ET	Cyl. 3 : DYN 40 L - 700 bar	ET	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas initial temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case	1	horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Repeatability test (=Ref case)	2	horizontal	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Initial pressure change	3	horizontal	3mm	100 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Inlet gas T° change	4	horizontal	3mm	20 barg	20°C	-40°C	8 g/s	SOC=100% or Tgas>85°C
Mass flow rate change	5	horizontal	3mm	20 barg	20°C	-20°C	2g/s	SOC=100% or Tgas>85°C
No temp control	6	horizontal	3mm	20 barg	20°C	No cooling	2g/s	SOC=100% or Tgas>85°C
Temperature shift	7	horizontal	3mm	20 barg	0°C	-40°C	8 g/s	SOC=100% or Tgas>85°C
Diameter change	8	horizontal	10mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C
Initial pressure change	9	horizontal	3mm	5 barg (if possible)	20°C	-20°C	8 g/s	SOC=100% or Tgas>85°C

Temperature Disparities – Filling: these tests are focusing on heterogeneous conditions and having the other parameters varying. Only some of the tests are done, as others where done in the previous table. The main variation factor here is the injection diameter and the flow rate, as shown in Table 19.

Table 19: DYN40L Temperature Disparities testing at ET

Bank_4_DYN_40L_ET	Cyl. 3 : DYN 40 L - 700 bar	ET	Fillings					
	Test number	Position of tank	Injector diameter	Initial pressure	Initial cylinder and gas initial temperature	Inlet gas temperature	Average mass flow during filling	End of fill criterion
Ref case (D1 - F1)		horizontal	3mm	20 barg	20°C	Tin1 : -20°C	8 g/s	SOC=100% or Tgas>85°C
D1 - F2		horizontal	3mm	20 barg	20°C	Tin1 : -20°C	2 g/s	SOC=100% or Tgas>85°C
D2 - F1	3	horizontal	6mm	20 barg	20°C	Tin1 : -20°C	8 g/s	SOC=100% or Tgas>85°C
D2 - F2	4	horizontal	6mm	20 barg	20°C	Tin1 : -20°C	2 g/s	SOC=100% or Tgas>85°C
D3 - F1		horizontal	10mm	20 barg	20°C	Tin1 : -20°C	8 g/s	SOC=100% or Tgas>85°C
D3 - F2	6	horizontal	10mm	20 barg	20°C	Tin1 : -20°C	2 g/s	SOC=100% or Tgas>85°C

Energy Based – Filling: these tests are focusing on the cooling profile. They compare different way to provide the same amount of energy in the tank. These cases were only defined to be performed at JRC, which had the capacity to perform these tests as additional tests.

Defuelling: these tests are studying the thermal behaviours during a defuelling. They follow the previous fuellings, we have the reference case, a repeatability case, and a serie of different defuelling flow rates, as well as a defuelling with a lower ambient temperature, as shown in Table 20

Table 20: DYN40L Defuelling testing at ET

Bank_4_DYN_40L_ET	Cyl. 3 : DYN 40 L - 700 bar	ET	Emptyings				
	Test number	Position of tank	Injector diameter	Initial SOC	Initial cylinder and gas temperature	Average Mass flow	End of defueling criterion
Ref case	1	horizontal	3mm	100%	20°C	Constant 0.376g/s	pressure < 20 barg or Tgas<-40°C
Repeatability (=ref case)	2	horizontal	3mm	100%	20°C	Constant 0.376 g/s	pressure < 20 barg or Tgas<-40°C
	3	horizontal	3mm	100%	20°C	Constant 0.5g/s	pressure < 20 barg or Tgas<-40°C
	4	horizontal	3mm	100%	20°C	Constant 0.188g/s	pressure < 20 barg or Tgas<-40°C
	5	horizontal	3mm	100%	20°C	Constant 0.125g/s	pressure < 20 barg or Tgas<-40°C
	6	horizontal	3mm	100%	20°C	1.5g/s for 500s then 0.2g/s for the rest of the defueling	pressure < 20 barg or Tgas<-40°C
	7	horizontal	3mm	100%	20°C	0.2g/s for 3100s then 1.5g/s for the rest of the defueling	pressure < 20 barg or Tgas<-40°C
	8	horizontal	3mm	100%	-20°C	Constant 0.125g/s	pressure < 20 barg or Tgas<-40°C
	9	horizontal	3mm	100%	20°C	Constant 0.188g/s	pressure < 5 barg (if possible) or Tgas<-40°C

A total of 12 fuellings and 12 defuellings (including 9 defined in table) have been performed on Type III and Type IV short tanks at the JRC test facility. The detail of the experimental campaign is given in the following sections.

4 MEASUREMENT POINTS

We will detail here the different parameters that were measured during the experiments. More details will be given for each facility in the following sections. We present below a schematic of the different measurement points, in green temperature measurements, in yellow the pressure ones and in blue the mass measurements.

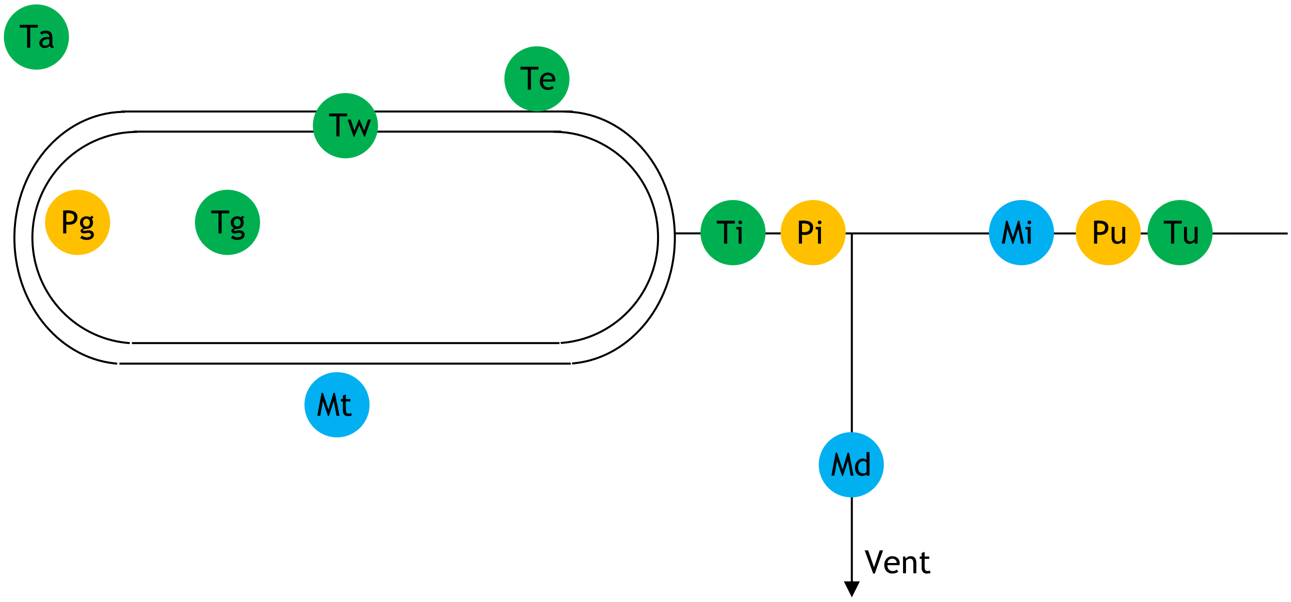


Figure 11: Position of the measurement points

We give here an explanation of each of the measured values and a summary in Table 21.

4.1 Temperature measurements

These are the most valuables measurements of the experiments, as the thermal behaviours are the key observed parameters. They are also the measurements points that required the most engineering to be installed:

- Ta , ambient temperature, each test facility was equipped with 2 measurements, one in the area at the front of the tank and the other at the back. This gave an ambient temperature redundancy and was also useful for testing performed outdoors or with a ventilation system.
- Tu : upstream temperature, in order to have a redundant information on the inlet gas temperature and have a first evaluation of the pipe thermal inertia impact a temperature measurement of the gas in the line was placed about 1-2 meters before the tank.
- Ti : inlet temperature, this is the key measurement of inlet gas temperature used within CFD and simple models. It is the measure of the gas temperature a few centimetres before entering the tank.

- Tg : gas temperature, in order to measure the temperature of the gas at different positions in tank, 3 different thermocouple trees were used in the different tanks. According to simulation findings, the measurements were done only in the vertical plane of the tank.
- Tw : wall temperature, each of the cylinders were built integrating 30 thermocouples between the liner and the composite fiber wrapping. This required a hard construction and pre-testing work by the cylinders manufacturers. On some of the experiments a few thermocouples are not recorded because they were broken during transportation
- Te : external wall temperature, in addition of the previous tank temperature measurements, 6 thermocouple were sticked on the external wall of the cylinders. 3 of them on the top and 3 of them on the bottom, with aluminium tape, all on the vertical plane.

4.2 Pressure measurements

The pressure measurement is used for filling regulation and recording the state of tank at different position during the fuelling:

- Pu : upstream pressure, in order to have a redundant information on the inlet gas pressure and evaluate the line pressure drop a pressure measurement was placed about 1-2 meters before the tank, at the same location as Tu.
- Pi : inlet pressure, this is the measurement of inlet gas pressure used within CFD and simple models as input. It is the measure of the gas temperature a few centimetres before entering the tank.
- Pg : gas pressure, this measurement is done in the back of the tank mounted on the thermocouple tree. Compared to Pi, it helps to evaluate the pressure drop at the injection.

4.3 Mass measurements

The mass measurement is mainly a mass flow measurement used in the models and to record one of the parameters varying in the test tables:

- Mi : inlet mass flowrate, this is the measurement of the mass flowrate entering the tank. Some of the tests were done controlling the mass flow rate delivered, other using a simple correlation between pressure ramp and average mass flowrate.
- Md : defuelling mass flowrate, this is the measurement of the mass flowrate for the defuelling control. At JRC Mi was used for this purpose, at ET it was used for regulation and at AL-aT it was used with a flow orifice combination. It is one of the parameters of the test table.
- Mt : tank mass, only at AL-aT for short tanks a scale was installed under the tank to measure the mass inserted as an additional information.

4.4 Summary

Table 21: Summary of the different measurement points

Measurement	DYN40L	HEX36L	HEX531L
Tambiant	2 measurements front and back of the tank	2 measurements front and back of the tank	2 measurements front and back of the tank
Tupstream	1 measurement in the line 1-2m upstream of tank	1 measurement in the line 1-2m upstream of tank	1 measurement in the line 1-2m upstream of tank
Tinlet	1 measurement in the line at tank inlet	1 measurement in the line at tank inlet	1 measurement in the line at tank inlet
Tgas	7 measurements on vertical plane in the tank	7 or 10 measurements on vertical plane in the tank	5 measurements on vertical plane in the back of tank
Twall	30 measurements between liner and composite wrapping (some broken)	30 measurements between liner and composite wrapping (2 broken)	30 measurements between liner and composite wrapping
Texternalwall	6 measurements on the tank surface (3 top / 3 bottom)	6 measurements on the tank surface (3 top / 3 bottom)	6 measurements on the tank surface (3 top / 3 bottom)
Pupstream	1 measurement in the line 1-2m upstream of tank	1 measurement in the line 1-2m upstream of tank	1 measurement in the line 1-2m upstream of tank
Pinlet	1 measurement in the line at tank inlet	1 measurement in the line at tank inlet	1 measurement in the line at tank inlet
Pgas	1 measurement in the back of the tank	1 measurement in the back of the tank	1 measurement in the back of the tank
Minlet	1 measurement in the fuelling line	1 measurement in the fuelling line	1 measurement in the fuelling line
Mdefuelling	1 measurement in the defuelling line (Mi used at JRC)	1 measurement in the defuelling line (Mi used at JRC)	1 measurement in the defuelling line
Mtank	None	1 scale under the tank only at AL-aT	None

5 TEST CAMPAIGN

We present the experimental testing report of each test laboratories in the following section.

5.1 Test campaign on Type III short tank at JRC

5.1.1 Introduction

This section summarizes briefly the experiments performed by JRC on the type III tank as laid out in the program of WP4 of HyTransfer project. This set of experiments will be used for the validation of different simulation models (CFD) developed by the Joint Research Centre (JRC) and Air Liquide (AL).

The preparation of the experimental setup, the execution of the test plan, and an example of results obtained are shown in this report. The full results data have been sent in digital format to the partners involved in the experiments and simulations

5.1.2 Preparation of the tests

Dynetek tank (T1602, Figure 12 see left) was delivered at JRC facilities on 3rd July. Thermocouples placed between liner and wrapping were checked. TC2, TC16 and TC19 were already broken.

Once the reference mark for the position of the thermocouples was found (In the vertical plane, at the inlet and indicating the top of the tank, see Figure 12), the JRC-made thermocouple tree was placed inside the tank and the locations of the thermocouples between liner and wrapping were checked, to avoid possible future confusion during the analysis of the data.

Figure 12 : Reference mark in the inlet boss

Calibration of pressure and temperature measurement devices was performed prior to the beginning of the tests.

In the case of the calibration of the pressure transducer, this is the procedure that was followed:

1- To check mA output of pressure transducers with Keithley 2100, at 0 and 1000 bar, using Wika Calibrator as reference

2- Values received for Zero and Max are then inserted into MTL system with Bürster calibrated mA source

3- Measured values are then corrected in the Variable editor in Labview to give correct values.

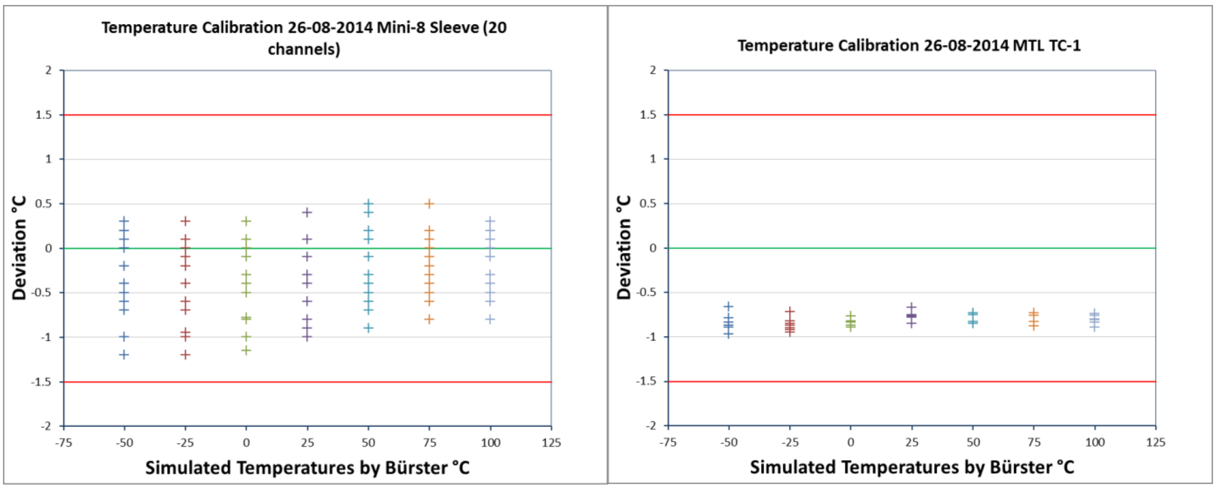
The results of these calibrations are shown in

Table 22: Results from pressure transducers calibration

	1				2				3			
	P (barg)	mA	P (barg)	mA	Bürster	Measured	Bürster	Measured	Bürster	Measured	Bürster	Measured
IP1	0.0	4.01	1000.0	19.98	4.01	1.1	19.98	1005.0	4.01	0.0	19.98	1000.0
IP2	0.0	3.98	1000.0	19.82	3.98	-0.8	19.82	996.0	3.98	0.0	19.82	1000.0
TP	0.0	3.98	1000.0	19.80	3.98	-0.8	19.80	998.0	3.98	0.0	19.80	1000.0

In the case of the thermocouples, because it was not possible to perform a standard calibration due to geometrical reasons, what was performed was an identification of the deviation in the interpretation of the electric signals done by the acquisition system.

The identification of these deviations was done by means of a calibrated mA source (Bürster). There are three different acquisition systems in the GasTef facility, Mini-8 (with 32 channels, used for thermocouples located between liner and wrapping), MTL TC-1 (8 channels, for the internal temperatures) and MTL-TC2 (8 channels, external temperatures). The deviations observed are depicted in Figure 2, the points represented in Figure 13 are the measurements recorded from every channel. In the case of the Mini-8 only 20 channels were analyzed, since only these 20 were used during the tests. These deviations have not been corrected.



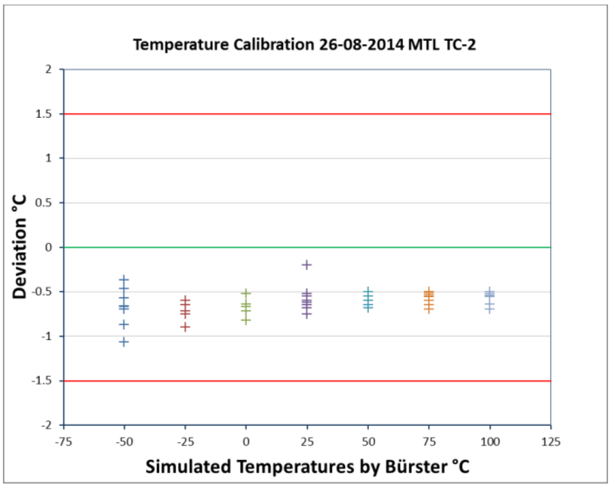


Figure 13: Deviations identified in thermocouples data acquisition systems

On 25th September, one end aluminum plug from Dynetek, 12 O-rings, 12 back-up rings, two modified inlet plugs, two 3mm injectors, two 6mm injectors and two radial injectors (4x3mm) were delivered at JRC facilities.

According to the specifications of the manufacturer, lubricant grease was used in the front and rear plugs in order to avoid the seizing up between plugs and bosses (Figure 14)

Figure 14: Front plug and lubricant grease

During the preparation of the tank some thermocouples placed between liner and wrapping broke (see Table 23). These thermocouples are extremely fragile due to their thickness (0.5 mm), and they all broke in the same place (where the thermocouple wire connects with the cable, see Figure 15).

Figure 15: Thermocouples broken

Six thermocouples were placed on the external wall of the tank (three on the bottom and three on the top), these thermocouples were attached to the tank using a piece of rubber (which improves the thermocouple contact with the surface of the tank and provide insulation from the environment) and tape, as can be observed in Figure 16.

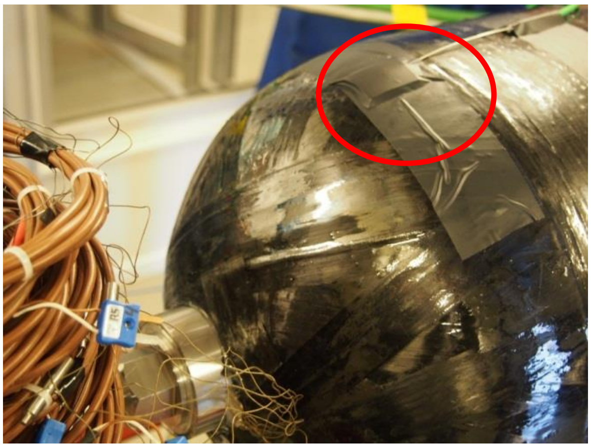


Figure 16: External thermocouple

The positions of these thermocouples as well as the location of the ones placed between wrapping and liner are shown in

(sizes in mm). The internal gas temperature were measured using the JRC thermocouple tree, the location of the six thermocouples is shown in

(sizes in mm).

All the sensors that have been collecting data during the experiments are shown in the Table 23, as well as the abbreviation used in the file were the data is recorded. The data don't appear in this order in the file recorded.

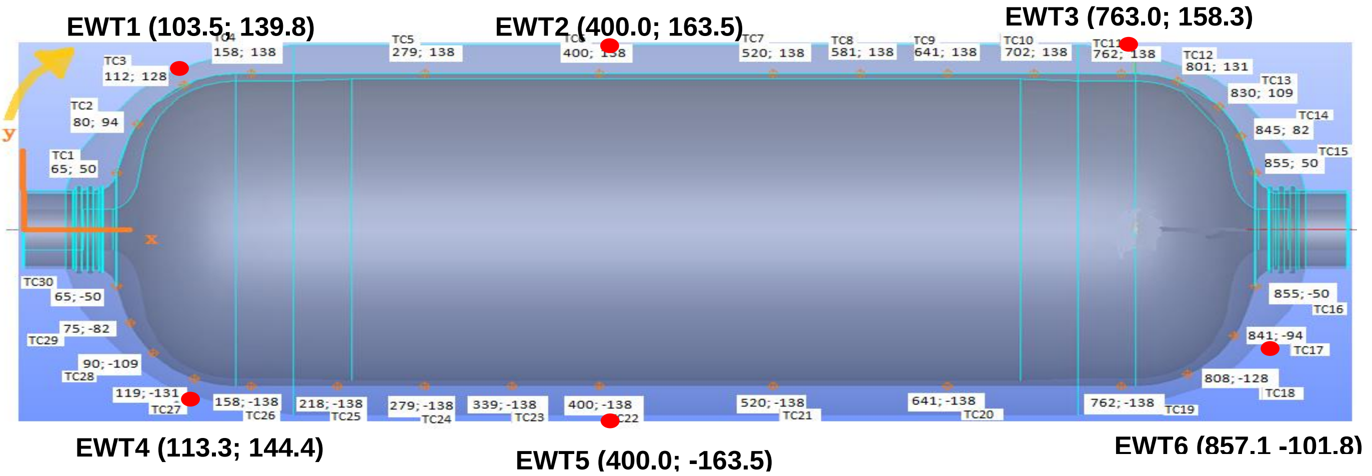


Figure 17: Position of External Thermocouples (EWT) and thermocouples placed between liner and wrapping (TC)

Please place a vertical arrow here to show the vertical plan where will be located the TC. Arrow should : 1/ be on the vertical plan, 2/ show the upper direction, 3/ be at this same side of the tank (inlet)

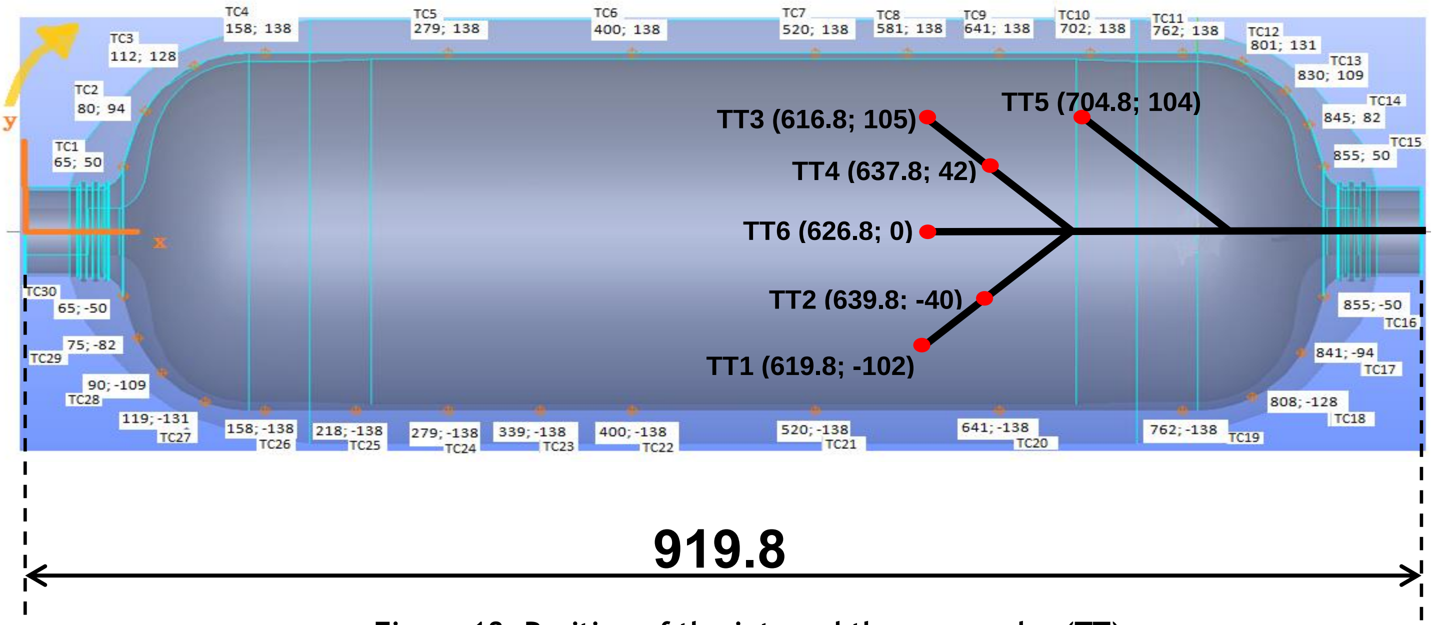


Figure 18: Position of the internal thermocouples (TT)

Table 23: Identification of sensors at GasTef facility during HyTransfer tests

Measurement	Name	Description	Location at JRC	Observations
Pressure	IP1	Inlet pressure	3.5 m from the inlet	
Temperature	IT1	Inlet temperature	2.5 m from the inlet	
Pressure	IP2	Inlet pressure	30 cm from inlet	
Temperature	IT2	Inlet temperature	30 cm from inlet	
Pressure	TP	Tank pressure	Rear of the tank	

Temperature	TT1	Internal gas temperature	See drawings	
Temperature	TT2	Internal gas temperature	See drawings	
Temperature	TT3	Internal gas temperature	See drawings	
Temperature	TT4	Internal gas temperature	See drawings	
Temperature	TT5	Internal gas temperature	See drawings	
Temperature	TT6	Internal gas temperature	See drawings	
Temperature	EWT1	External Wall Temperature	See drawings	
Temperature	EWT2	External Wall Temperature	See drawings	
Temperature	EWT3	External Wall Temperature	See drawings	
Temperature	EWT4	External Wall Temperature	See drawings	
Temperature	EWT5	External Wall Temperature	See drawings	
Temperature	EWT6	External Wall Temperature	See drawings	
Temperature	AT1	Ambient Temperature	Rear of the sleeve	
Temperature	AT2	Ambient Temperature	Front of the sleeve	
Temperature	TC1	Composite-Liner temperature	See drawings	Broken during tests
Temperature	TC2	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC3	Composite-Liner temperature	See drawings	
Temperature	TC4	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC5	Composite-Liner temperature	See drawings	
Temperature	TC6	Composite-Liner temperature	See drawings	
Temperature	TC7	Composite-Liner temperature	See drawings	
Temperature	TC8	Composite-Liner temperature	See drawings	
Temperature	TC9	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC10	Composite-Liner temperature	See drawings	
Temperature	TC11	Composite-Liner temperature	See drawings	
Temperature	TC12	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC13	Composite-Liner temperature	See drawings	
Temperature	TC14	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC15	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC16	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC17	Composite-Liner temperature	See drawings	
Temperature	TC18	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC19	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet
Temperature	TC20	Composite-Liner temperature	See drawings	
Temperature	TC21	Composite-Liner temperature	See drawings	
Temperature	TC22	Composite-Liner temperature	See drawings	
Temperature	TC23	Composite-Liner temperature	See drawings	
Temperature	TC24	Composite-Liner temperature	See drawings	Not working. Not in the Data sheet

Temperature	TC25	Composite-Liner temperature	See drawings	
Temperature	TC26	Composite-Liner temperature	See drawings	
Temperature	TC27	Composite-Liner temperature	See drawings	
Temperature	TC28	Composite-Liner temperature	See drawings	
Temperature	TC29	Composite-Liner temperature	See drawings	
Temperature	TC30	Composite-Liner temperature	See drawings	
Mass	M	Total mass	50 cm from inlet	
Mass flow	MF	Mass flow	50 cm from inlet	

5.1.3 Tests plan

Three different fuellings, and three different defuellings were defined within the test plan. The most important parameters are shown in Table 24 and Table 25.

Table 24: Main parameters in fuelling tests

Fuelling	Test	Injector diameter	Initial pressure	Initial temperature (gas and tank)	Inlet gas temperature	Average mass flow	End of fill criterion
Ref case	1	3mm	20 barg	20°C	Tin1 : -20°C	8 g/s	SOC=100% or Twall>85 °C
More cooling during second half	2	3mm	20 barg	20°C	Tin = 0°C for 75s then Tin = -40°C for 75s	8 g/s	time = 150s
More cooling during first half	3	3mm	20 barg	20°C	Tin = -40°C for 75s then Tin = 0°C for 75s	8 g/s	time = 150s

Table 25: Main parameters in defuelling tests

Defuelling	Test	Injector diameter	Initial SOC	Initial temperature (gas and tank)	Average mass flow	End of defuelling criterion
Ref case	1	3mm	100%	20°C	0.376 g/s	Pressure < 20 barg or Tgas<-40°C
	2	3mm	100%	50°C	0.376 g/s	Pressure < 20 barg or

						Tgas<-40°C
	3	3mm	100%	20°C	1.5g/s for 500s then 0.2g/s for the rest of the defuelling	Pressure < 20 barg or Tgas<-40°C

5.1.4 Results

On 7th October the test campaign started. More than 20 preparatory tests have been performed in order to get the right settings in the GasTef facility (compressor, cooling system, etc.) to realize the different fuelling and defuelling conditions as specified in the HyTransfer test plan.

At the beginning of the tests, 20 out of 30 thermocouples placed between liner and wrapping were working, however, during the performance of the tests, thermocouple TC1 was broken, so in some tests the data from this thermocouple is missed.

Table 26 and Table 27 show the parameters values obtained during the experimental tests. The average mass flow was calculated using the initial and final SoC and the filling time. The SoC was calculated using the NIST tables, pressure of the tank and average values of the temperatures inside the tank (TT1, TT2, TT3, TT4 and TT6) at the beginning and at the end of every test. For these calculations, except at the end of the defuelling, the temperatures inside the tank were homogeneous.

Table 26: Main parameters values obtained during fuelling tests

Fuelling	Test	Initial pressure	Initial temperature (gas and tank)	Inlet gas temperature	Average mass flow	SoC
Ref case	1	19.7 barg	20.7°C	Tin1 : -20.4°C	7.96 g/s	99.2 %
More cooling during second half	2	20.4 barg	22.7°C	Tin = 0.1°C for 60s then Tin = -31.9°C for 95s	7.8 g/s	99 %
More cooling during first half	3	20.8 barg	23.1°C	Tin = -31.7°C for 75s then Tin = -2°C for 75s	8.2 g/s	98.5 %

Table 27- Main parameters values obtained during defuelling tests

Defuelling	Test	Initial SOC	Initial temperature (gas and tank)	Average mass flow	Observations
Ref case	1	96.8	23.5°C	0.368 g/s	
	2	100.3	48.5°C	0.376 g/s	Fan working
	2	103.3	46.2°C	0.369 g/s	
	3	99.5	25.9°C	1.69g/s for 500s then 0.24g/s for the rest of the defuelling	

Next figures show the evolution of different parameters during fuelling and defuelling tests. The data represented can be identified in Figures 19 to Figure 31.

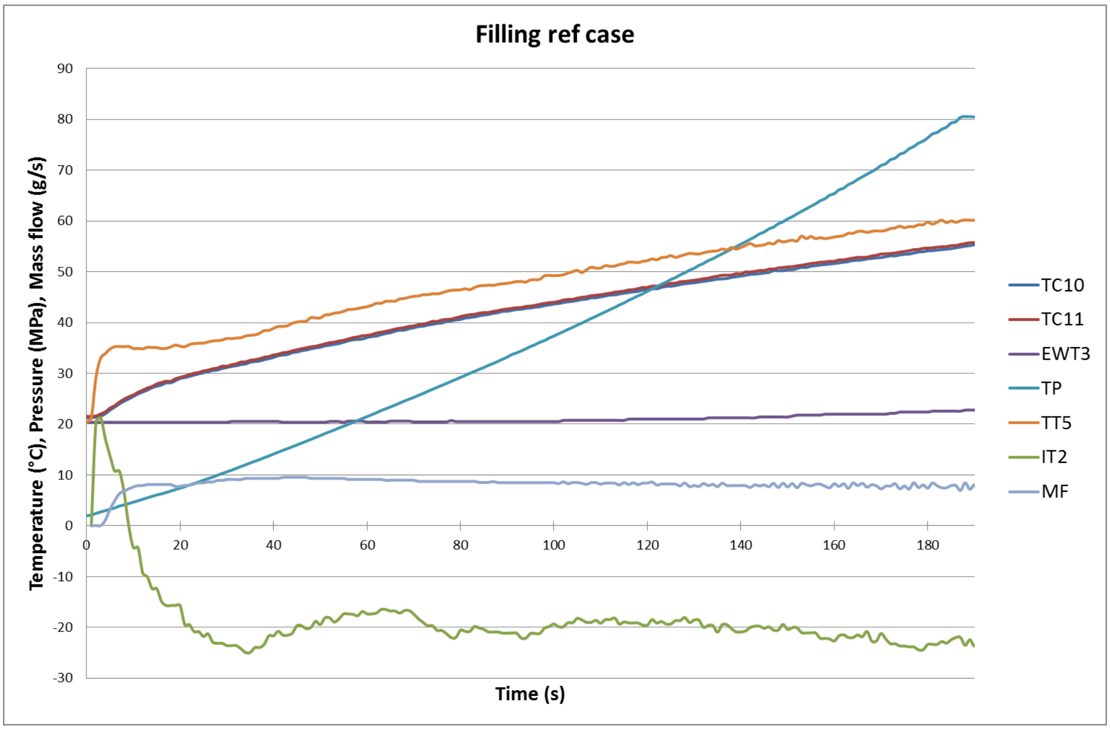


Figure 19: Filling reference case

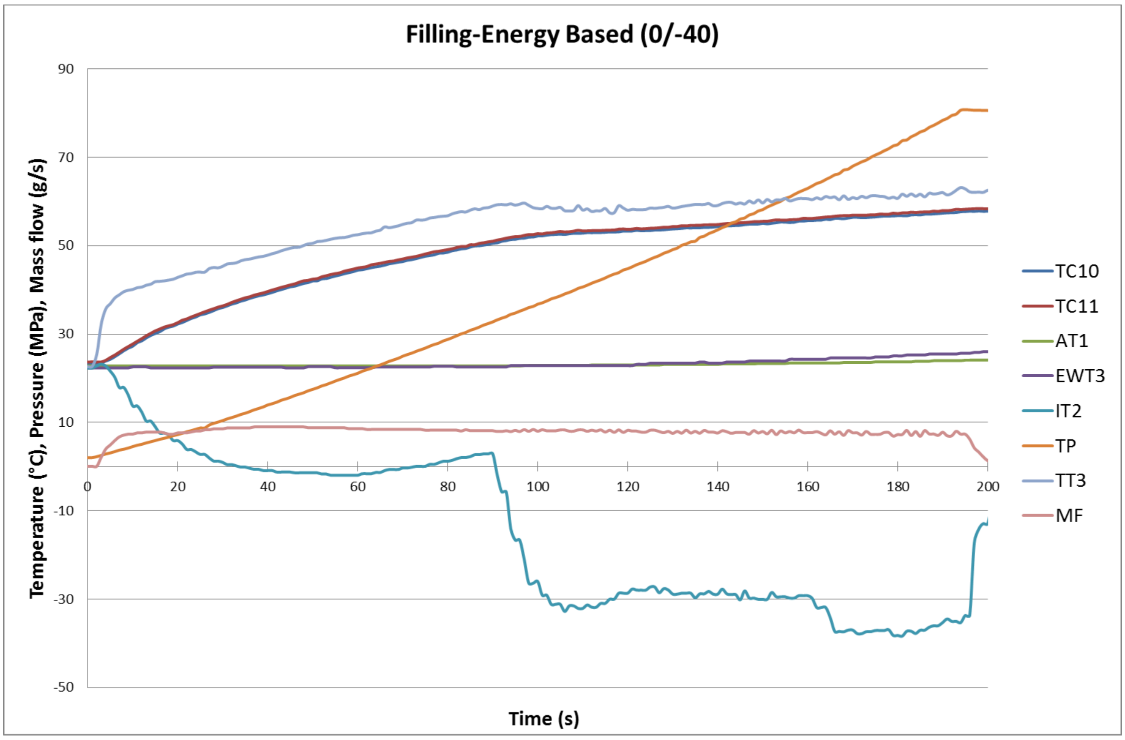


Figure 20: Filing energy based, first part of the filling at 0°C, second part of the filling at -40°C

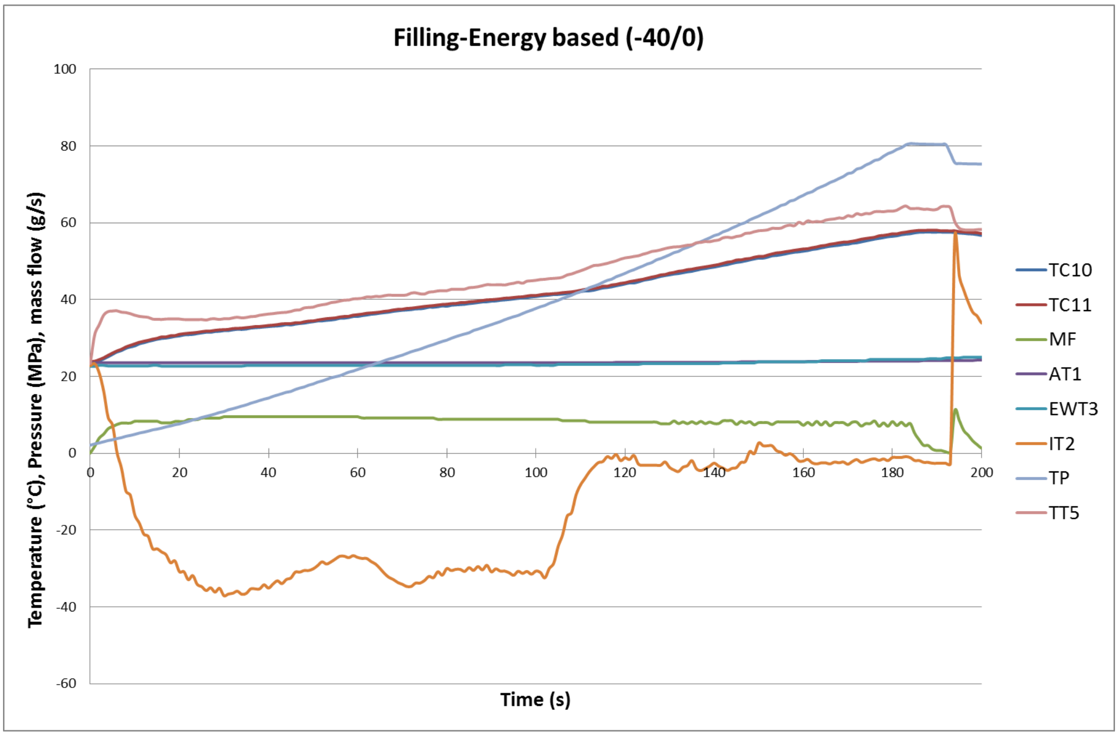


Figure 21: Filing energy based, first part of the filling at -40°C, second part of the filling at 0°C

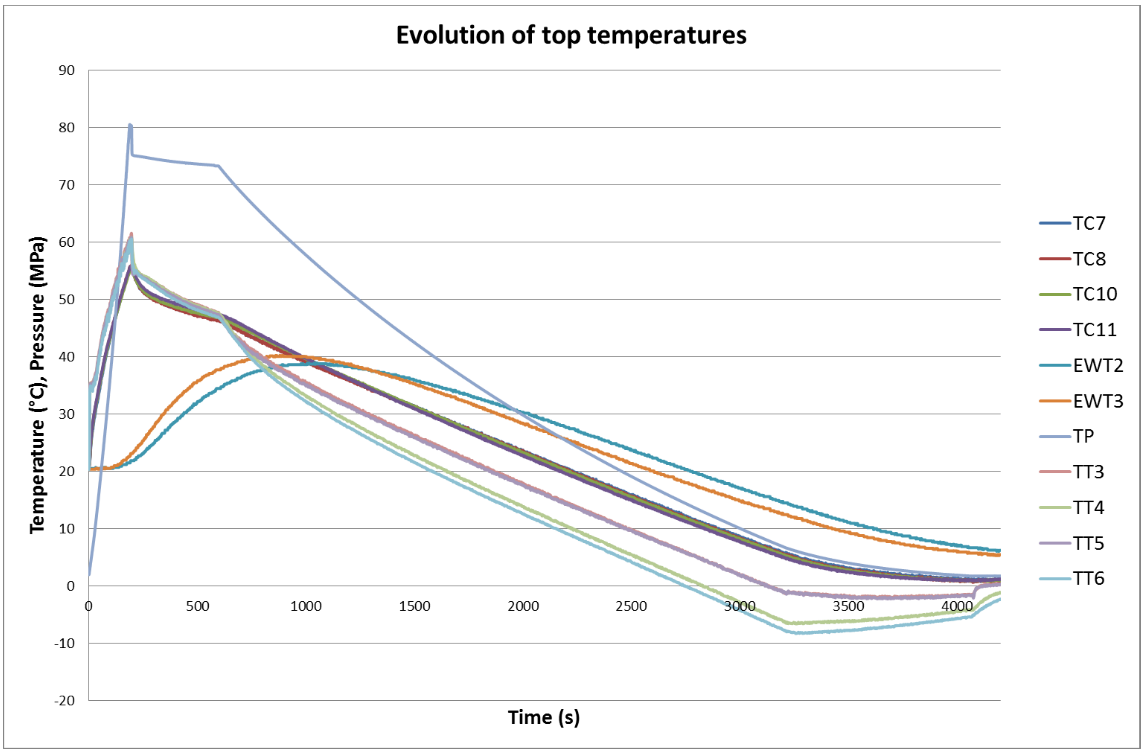


Figure 22: Evolution of top temperatures during a fuelling-defuelling cycle

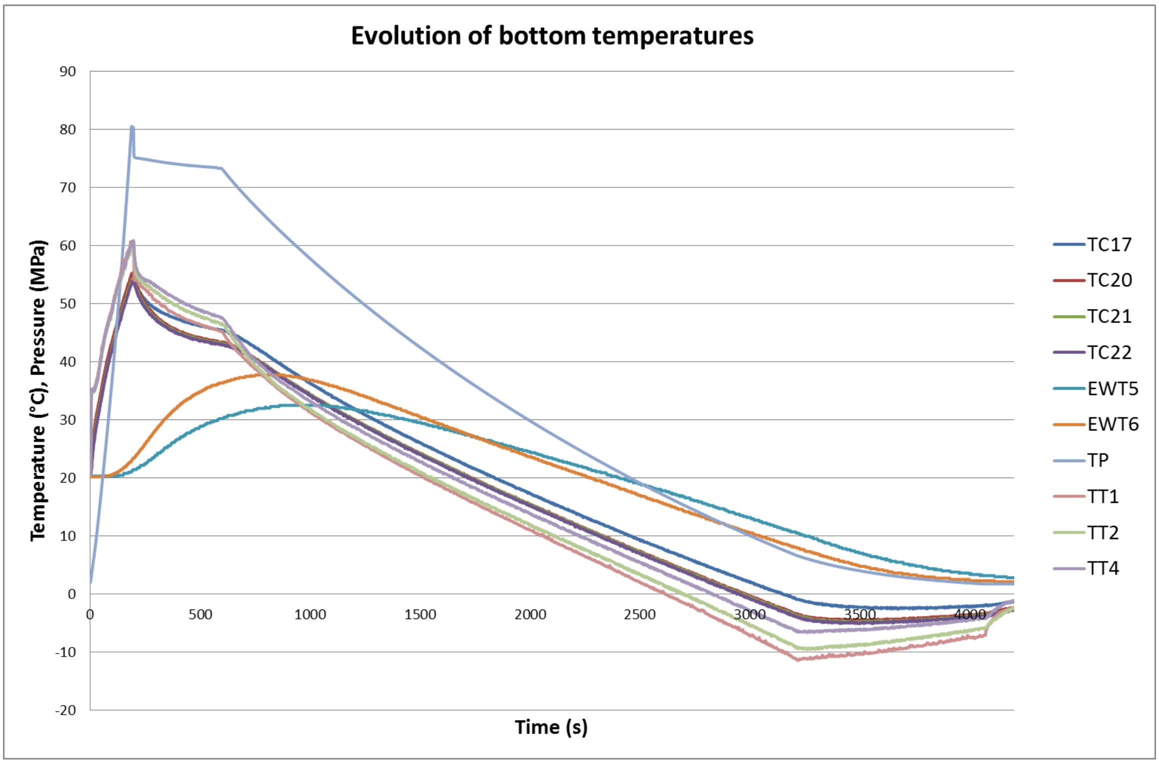


Figure 23: Evolution of bottom temperatures during fuelling-defuelling cycle

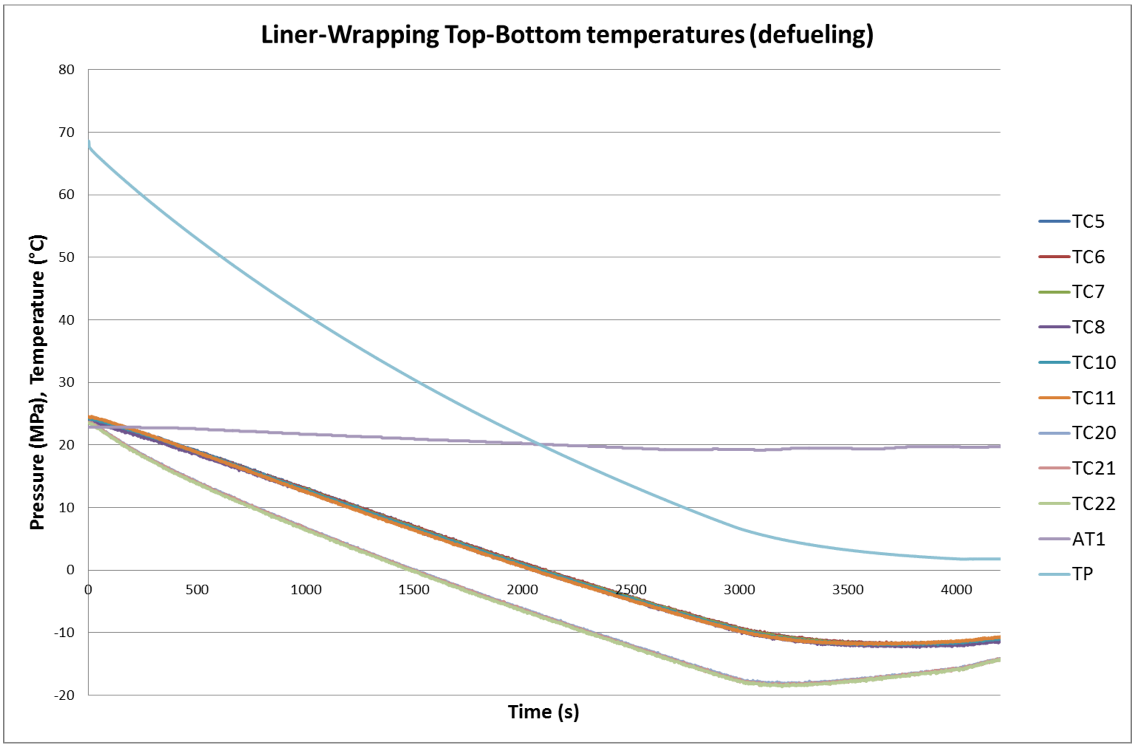


Figure 24: Evolution of liner-wrapping temperatures in central part of the tank (top and bottom) during ref. Defuelling

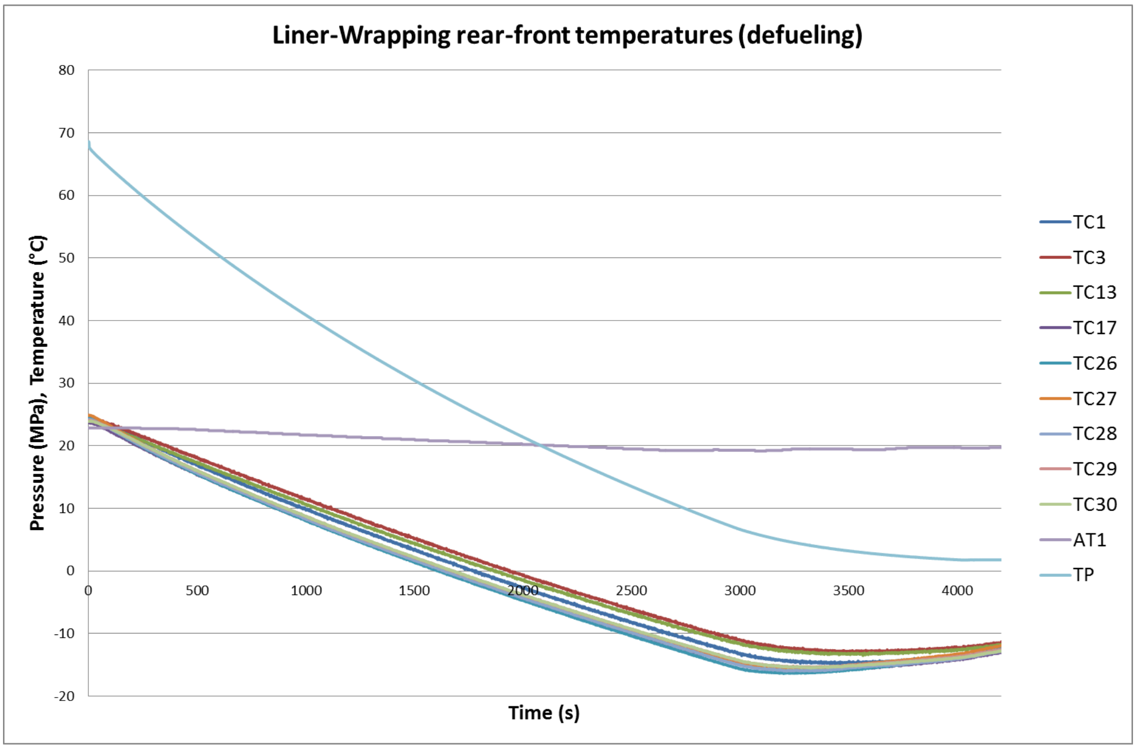


Figure 25: Evolution of liner-wrapping temperatures in the domes of the tank (front and rear) during reference defuelling

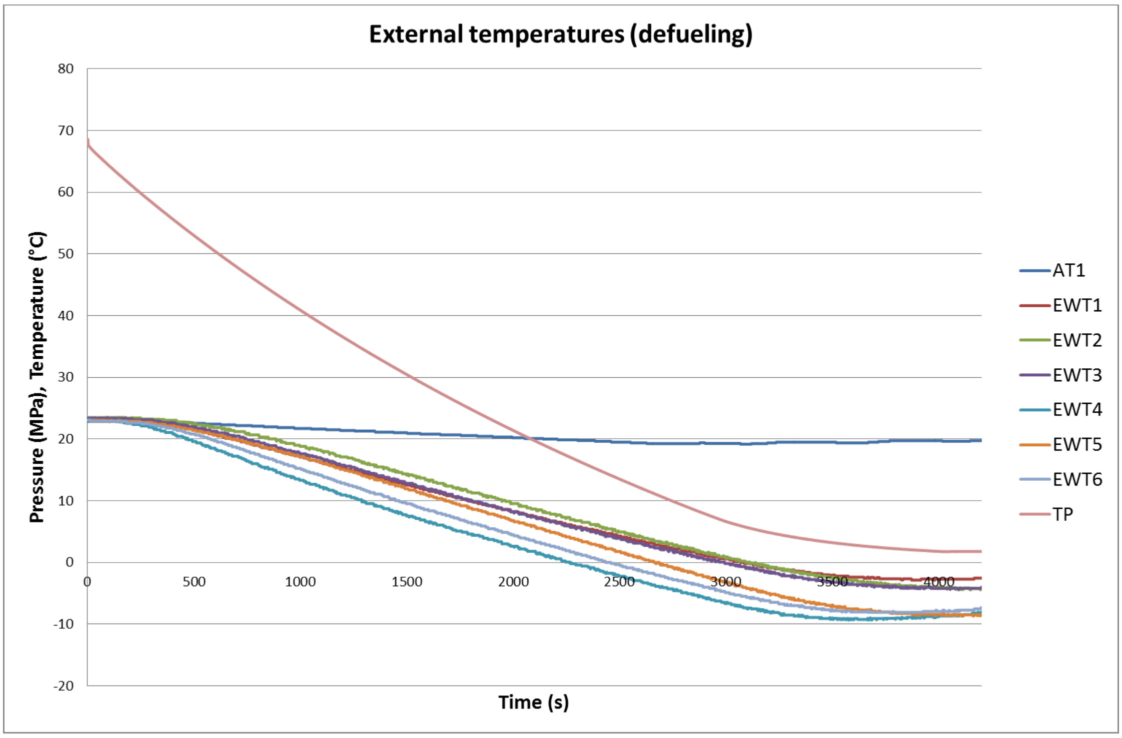


Figure 26: Evolution of external temperatures during reference defuelling

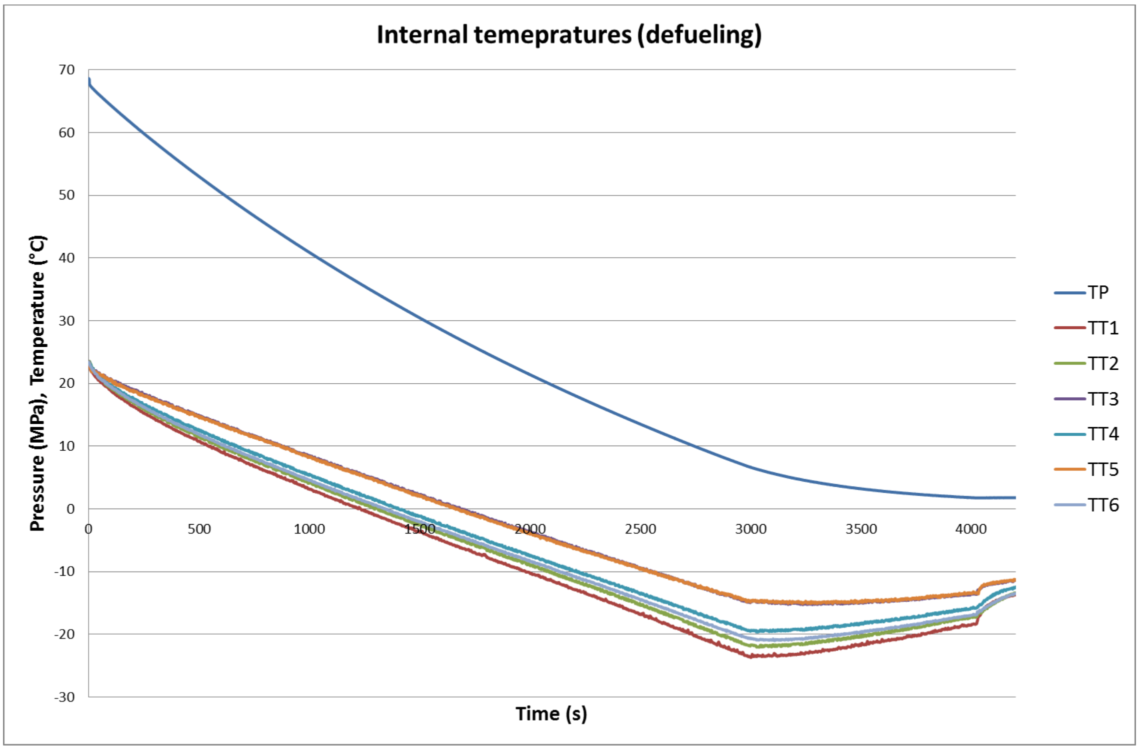


Figure 27: Evolution of internal temperatures during reference defuelling

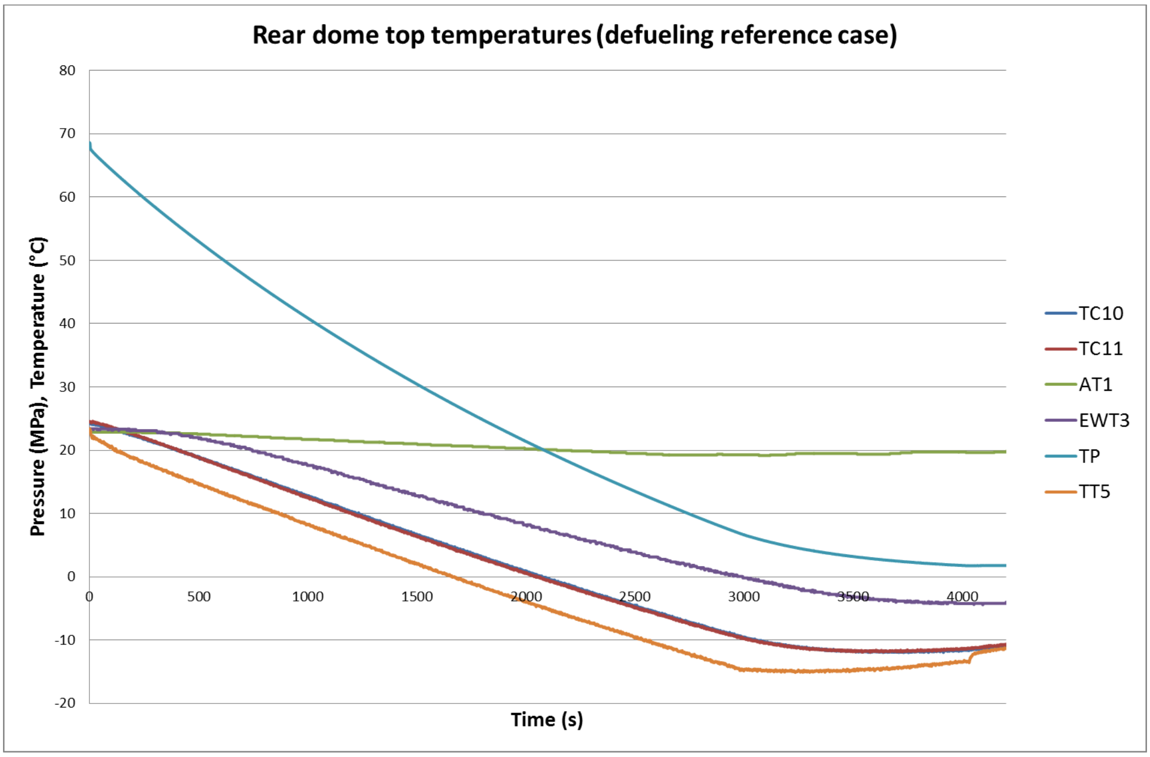


Figure 28: Evolution of dome top temperatures (internal and external) during defuelling reference case

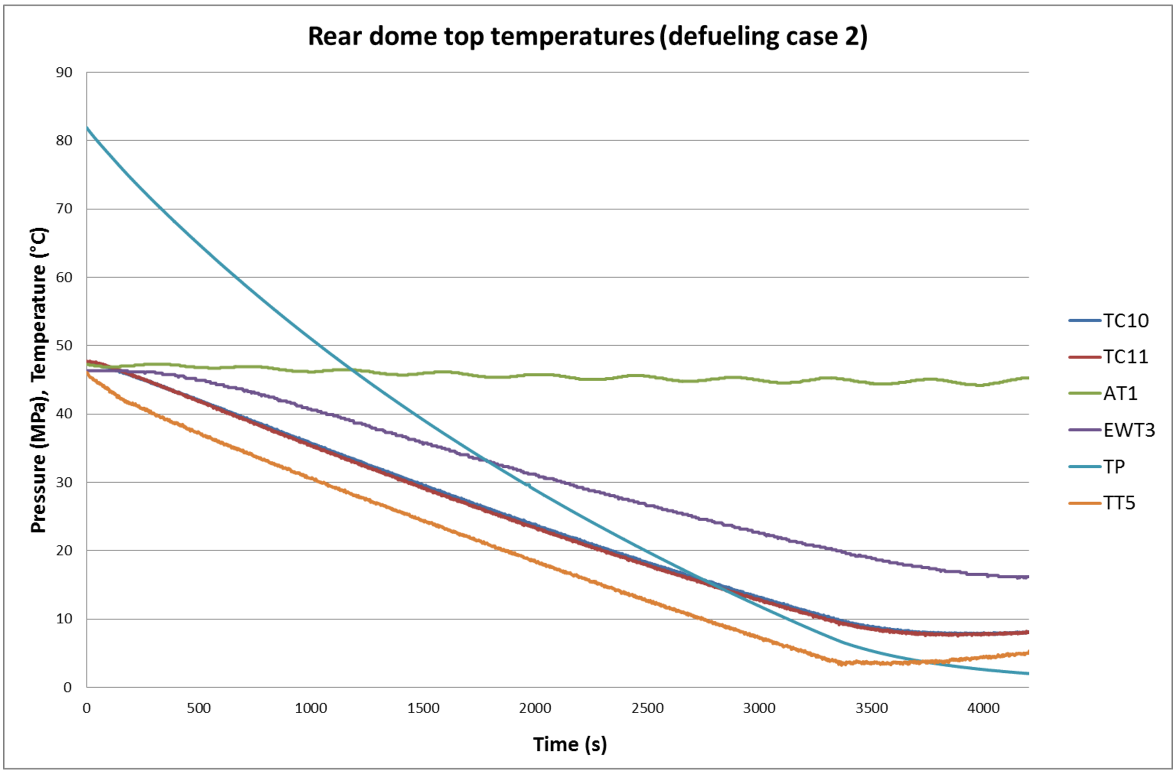


Figure 29: Evolution of dome top temperatures (internal and external) during defuelling case 2

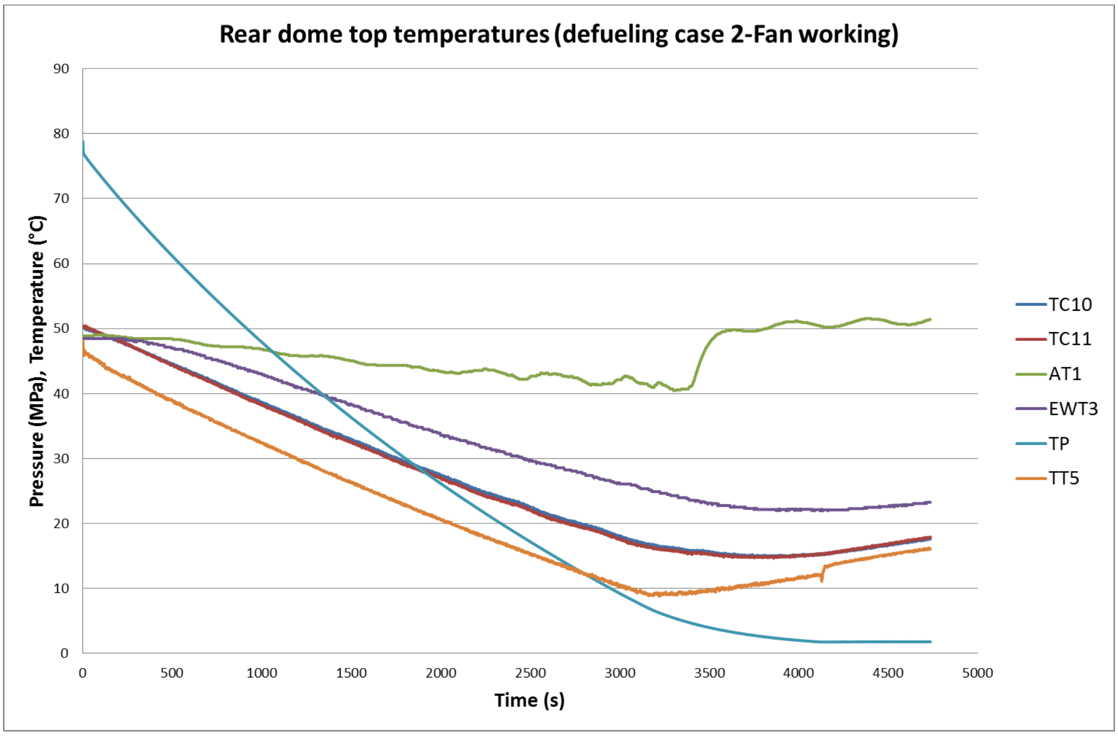


Figure 30: Evolution of dome tope temperatures (internal and external) during defuelling case 2 (fan working)

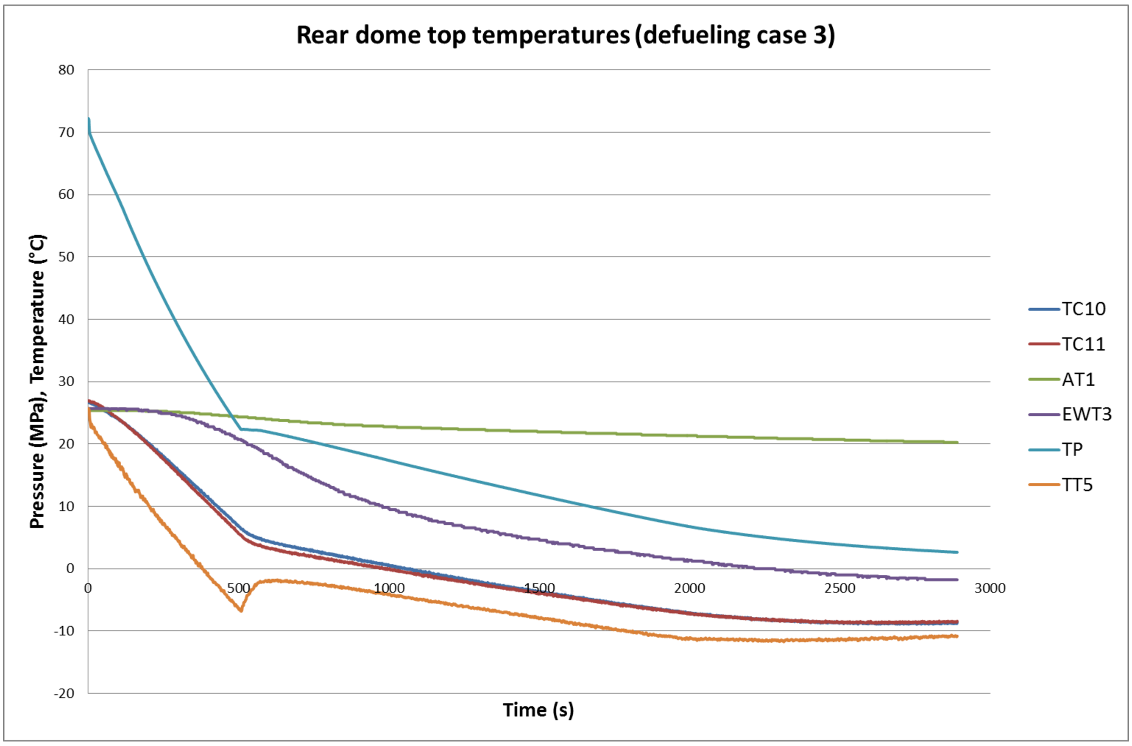


Figure 31: Evolution of dome tope temperatures (internal and external) during defuelling case 3

Once the tests were finished, an inspection of the tank was done in order to identify possible mistakes in the location/labelling of the thermocouples. It has been observed that the external thermocouple EWT1 was detached from the wall (the contact between thermocouple and wall was not 100% good). This problem has been solved prior to send the tank to ET.

5.1.5 Shipment to ET

The tank was packaged in its original box (with some modifications due to the thermocouple tree, see Figure 32) and sent to ET facilities on the 20th October. The thermocouple tree used for temperatures measurements of the gas inside the tank during JRC tests was also included in the shipment, as well as the external thermocouples (EWT1 to 6). Of course, thermocouples placed between liner and wrapping have been also sent. All these thermocouples have been sent placed in the same spot as they were when tests were performed at JRC GasTef facility.

In addition, 5 O-rings, 5 backup rings, one modified inlet plug (already placed in the tank), one 3 mm injector (already located inside the tank), one 6 mm injector and one radial injector were also included in the shipment.

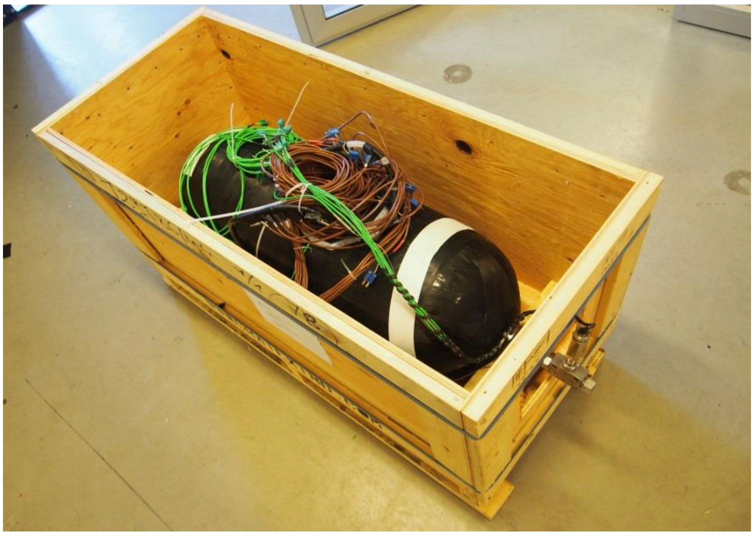


Figure 32: Packaging of Dynetek tank prior to be sent to ET

5.2 Test campaign on Type IV short tank at JRC

5.2.1 Introduction

This section is about the testing campaign of the Type IV tank. The preparation of the experimental setup, the execution of the test matrix and the results obtained from these tests are shown in the following chapters.

5.2.2 Preparation of tests

After a period in the Dutch customs, the Hexagon 36 litres Type IV tank identified with serial number SN 2707-002 was delivered at JRC facilities on 4th February 2015. Matching O-rings to make a proper sealing at the end plugs were as well delivered by Hexagon. Prior to that, in 2014 Air Liquide delivered the inlet plug with the different injectors required for the tests: ϕ 3 mm, ϕ 6 mm and 4 × ϕ 3 mm. The end plug assembly hosting the thermocouple tree has been built by the JRC in 2014.

At a first instance, signals from the thermocouples placed between liner and wrapping were checked and it was found that all of them were working properly. Reference markings for the position of the internal thermocouples, see Figure 33, were made by Hexagon at the tank rear boss (distinguished by blue colour). Based on that and after confirming it with Hexagon, the thermocouple tree was placed inside the tank and the location of the thermocouples between liner and wrapping were checked against the numbering in the design drawing to avoid any future confusion during the analysis of the data.

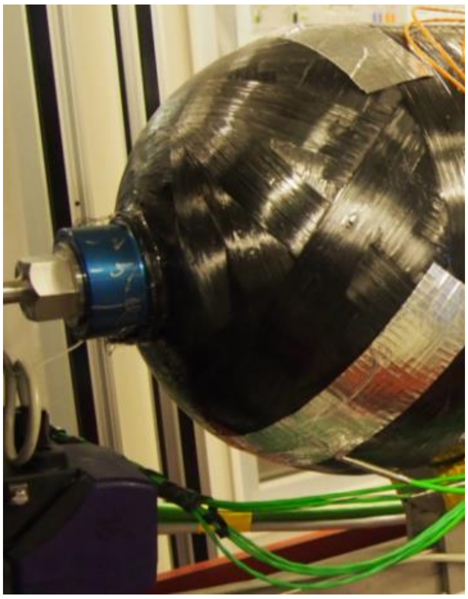
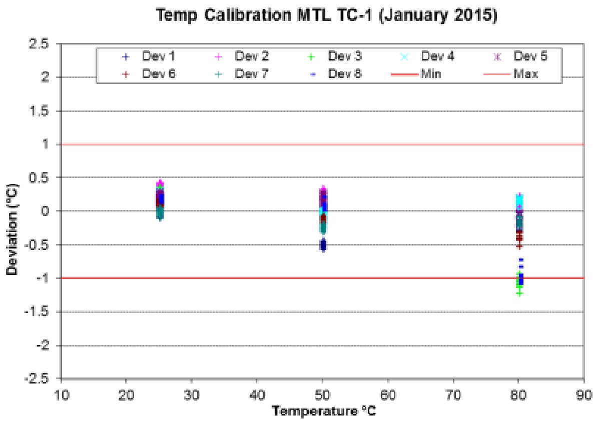
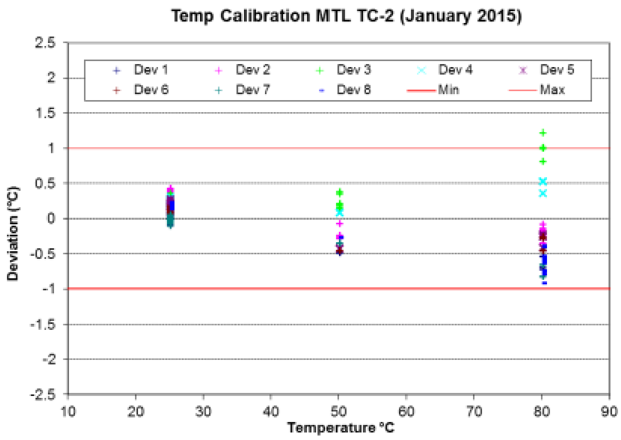


Figure 33: Reference marking in the rear boss

Calibration of pressure and temperature measurement devices was performed prior to the beginning of the tests. In the case of the thermocouples, more than a calibration, an identification of the deviation in the measurements was performed. There are different acquisition systems in GasTef facility, Mini-8 (with 32 channels, used for thermocouples located between liner and wrapping, TCs), MTL TC-1 (8 channels, for the internal temperatures measured with the thermocouple tree, TTs), MTL-TC2 (8 channels, external wall temperatures, EWTs) and the RTDs (6 channels for the control of the ambient temperatures, ATs).

A thermocouple bath was used for the MTL TC-1, MTL TC-2 and the RTDs. The calibration measurements were performed on January 2015. The bath was set at three different temperatures 25 °C, 50 °C and 80 °C and the deviation from the targeted temperature measured with the thermocouples was plotted. The deviations observed are depicted in Figure 34. The biggest deviation observed at highest temperatures has to do more with the difficulty of keeping the thermocouple bath at constant temperature than with the error of the thermocouples. In all cases, the thermocouple readings were within a ±1 ºC deviation while the RTDs within a ±0.5 ºC. For the Mini 8, the checking of the acquisition system of the thermocouples was performed in August 2014, prior to the test campaign of the Type III tank.





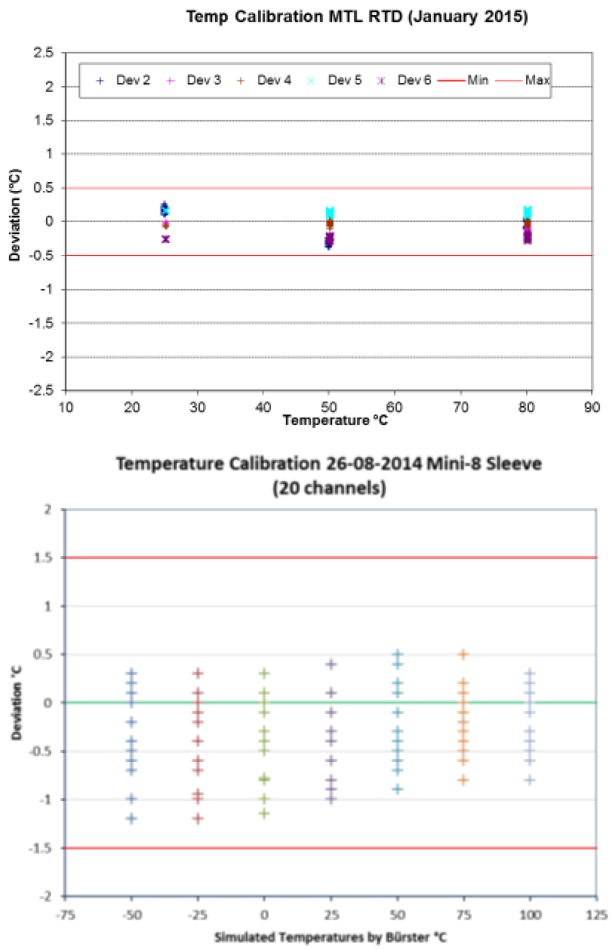


Figure 34: Reference marking in the rear boss

In the case of the calibration of the pressure transducers this is the procedure that was followed:

1) The mA output of pressure transducers was checked with Keithley 2100 digital multimeter, at 0 and 1000 bar, using Wika Calibrator as reference.
2) Values received for Zero and Max are then collected and inserted into MTL system with a voltage source.
3) Measured values are then corrected in the "Variable editor" in Labview © to give correct values and the appropriate measurements were checked up.

The results of these calibrations are shown in Table 28

Table 28: Pressure transducers calibration for HyTransfer

	1				2		3			
PT	Pressure (barg)	mA signal	Pressure (barg)	mA signal	Measured (0 barg)	Measured (1000 barg)	voltage source	Measured (0 barg)	voltage source	Measured (1000 barg)
10	0.00	3.998	1000.00	19.941	-5.50	950.05	3.998	0.00	19.941	1000.00

7	0.00	4.008	1000.00	19.970	-1.20	990.34	4.008	0.00	19.974	1000.00
14	0.00	4.004	1000.00	19.850	-0.52	1008.00	4.004	0.00	19.850	1000.00
15	0.00	3.977	1000.00	19.829	1.15	1009.30	3.977	0.00	19.829	1000.00
16	0.00	3.990	1000.00	19.820	0.18	1009.85	3.980	0.00	19.820	1000.00

After the calibration and after placing the thermocouple tree inside the tank, the other instrumentation necessary for the test was installed. First the pressure transducers were placed on the required positions and then six thermocouples were placed on the external wall of the tank (three on the bottom and three on the top). These thermocouples were attached to the tank using a reinforced aluminium tape which improves the thermocouple contact with the surface of the tank and do not provide insulation from the environment. The exact positions of the external wall thermocouples (EWTs) as well as the location of the thermocouples placed between the wrapping and the liner (TCs) are shown in Figure 35 (sizes in mm).

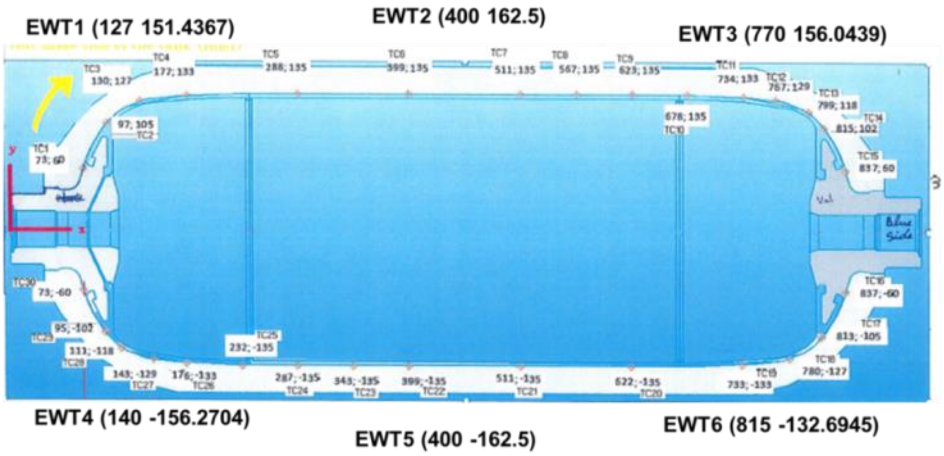


Figure 35: Position of External Thermocouples (EWT) and thermocouples placed between liner and wrapping (TC)

The internal gas temperature is measured using the JRC thermocouple tree; the location of the seven thermocouples (TTs) is shown in Figure 36.

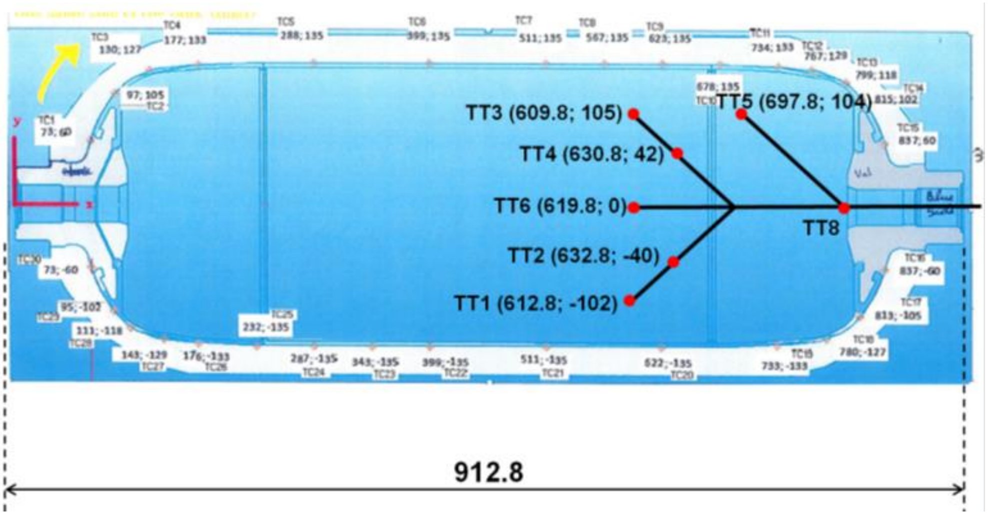


Figure 36: Position of the internal thermocouples (TT)

The sleeve temperature, the pressure inside the tank, the mass flow, the total mass and several pressures and temperatures along the inlet line were also measured during the test. The position of these sensors is shown in Figure 37. The tank was placed inside (and close to the inlet) of the 2 meters long and 0.5 meters diameter aluminium sleeve. During the test, a constant flow of N2 (of 75ml/min) was passing through it. The Resistant Temperature Detectors AT1 and AT2 measuring the temperature of the sleeve, were placed in the environment of the sleeve close to the tank's top bosses (as depicted in Figure 5). During all the tests we made sure that the fan inside the sleeve was not working.

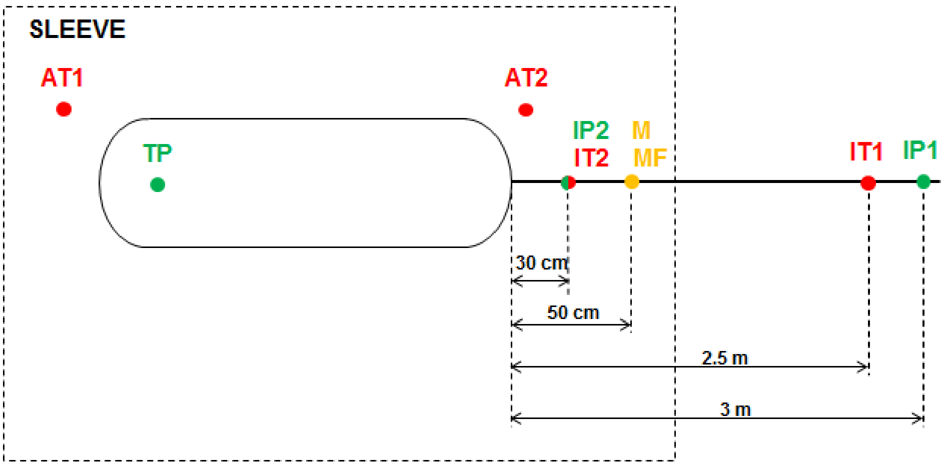


Figure 37: Position of the pressure, mass flow and auxiliary temperature measurement points for HyTransfer

In Figure 38, two detailed pictures of the instrumented tank entering the sleeve are shown. Note that in Figure 39 (right side) the position of the pressure transducer in 90° angle with the tank inlet is a confirmation of the proper placement of the thermocouple tree.

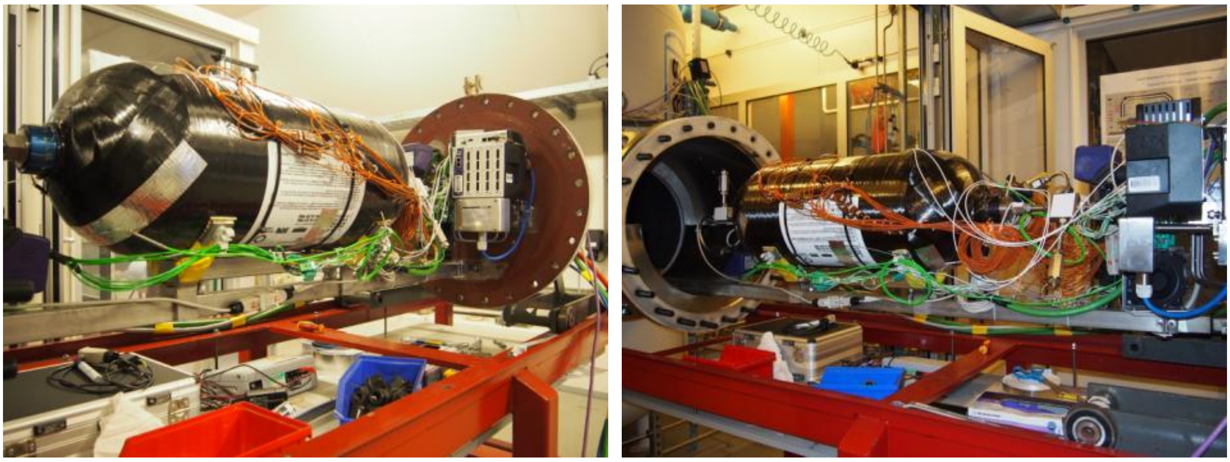


Figure 38: Instrumented Type IV tank entering the sleeve

5.2.3 JRC test matrix

The JRC test campaign for the HyTransfer Type IV tank consists on a test matrix of thirteen different fuelling and five different defuelling as agreed within the WP-4. The most important parameters are shown in Table 28 and Table 30.The inlet volume of the tank was 36 L and its nominal capacity 1.45 Kg.

Table 29: Test matrix in fuelling tests

Defuelling HEX 36 L	Injector diameter	Initial P	Initial T	Inlet gas T	Av. MF	End of fill criterion	Data file name
Ref case	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 1
Repeatability test (=Ref case)	3mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 2
Initial pressure change	3mm	100 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 3
Initial temp change	3mm	20 barg	40°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 4
Mass flow rate change	3mm	20 barg	20°C	-20°C	2g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 5
No temp control	3mm	20 barg	20°C	No cooling	2g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 6
Cooling during second half	3mm	20 barg	20°C	0°C for 75s -40°C for 75s	8 g/s	time = 150s	Fill-EB-Bank_3_HEX_36L_JRC-exp 2
Cooling during first half	3mm	20 barg	20°C	-40°C for 75s 0°C for 75s	8 g/s	time = 150s	Fill-EB-Bank_3_HEX_36L_JRC-exp 3
D2 - F1	6mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_3_HEX_36L_JRC-exp 3

D2 - F2	6mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_3_HEX_36L_JRC-exp 4
Diameter change	10mm	20 barg	20°C	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_3_HEX_36L_JRC-exp 7
D3 - F2	10mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_3_HEX_36L_JRC-exp 6
D2r - F2	4 x 3 mm	20 barg	20°C	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_3_HEX_36L_JRC-exp 7

Table 30: Test matrix in defuelling tests

Defuelling HEX 36 L	Injector diameter	Initial SOC	Initial T	Av. MF	End of fill criterion	Data file name
Ref case	3mm	100%	20°C	Constant 0.376g/s	P < 20 barg or Tgas<-40°C	Defuelling- Ref case-exp 1
Repeatability test (=ref case)	3mm	100%	20°C	Constant 0.376 g/s	P < 20 barg or Tgas<-40°C	Defuelling- Ref case-exp 2
Initial temperature change	3mm	100%	50°C	Constant 0.376 g/s	P < 20 barg or Tgas<-40°C	Defuelling- Init temp-exp 3
Lower mass flow rate	3mm	100%	20°C	Constant 0.188 g/s	P < 20 barg or Tgas<-40°C	Defuelling- Low MFR-exp 4
Higher mass flow rate	3mm	100%	20°C	Constant 2 g/s	P < 200 barg or Tgas<-40°C	Defuelling- High MFR-exp 5

5.2.4 Test results

The experimental campaign lasted about two months, from the 19th February to the 28th April 2015. In total, 60 fillings and 12 defuellings have been performed. These attempts were necessary to get the right settings in the GasTef facility (mainly related to the tuning of the compressor speed and of the cooling power) to fulfil the test targets as specified in the HyTransfer test plan.

Tables 31 and 32 show the parameter values achieved in the filling and defuelling tests. The SoC was calculated using the NIST tables, pressure of the tank (TP) and average values of the temperatures inside the tank (TT1, TT2, TT3, TT4 and TT6) at the beginning and at the end of every test. The average mass flow was calculated using the initial and final State of Charge (SoC) and the filling time.

In the defuelling tests, for the calculation of the emptying rate the linear emptying zone (from full tank down to 5 MPa) has been considered.

Table 31: Main parameters values obtained during fuelling tests

Defuelling Test number	Initial and Final P (bar)	Initial and Final Av. T (°C)	Inlet gas T (°C)	Average MF (g/s)	Filling time (s)	SoC (%)

Fill-SMV-Bank_3_HEX_36L_JRC-exp 1	20.7 855.1	21.6 73.8	-19.7	7.76	180	100.7
Fill-SMV-Bank_3_HEX_36L_JRC-exp 2	18.6 844.7	22.9 74.8	-18.7	7.75	179	99.7
Fill-SMV-Bank_3_HEX_36L_JRC-exp 3	109.7 836.7	21.7 70.7	-18.2	8.15	140	99.9
Fill-SMV-Bank_3_HEX_36L_JRC-exp 4	21.2 842.4	37.5 81.1	-18.5	7.97	171	98.3
Fill-SMV-Bank_3_HEX_36L_JRC-exp 5	19.9 822.8	20.1 62.3	-17.9	2.11	660	100.4
Fill-SMV-Bank_3_HEX_36L_JRC-exp 6	21.7 851.6	20.2 86.1	22.61	2.11	642	98.1
Fill-EB-Bank_3_HEX_36L_JRC-exp 2	20.6 712.1	20.2 68.4	0/-40	8.08	153	89.7
Fill-EB-Bank_3_HEX_36L_JRC-exp 3	20.8 702.4	19.0 72.7	-40/0	8.02	151	88.0
Fill-FTD-Bank_3_HEX_36L_JRC-exp 3	19.9 838.1	22.4 74.8	-18.8	8.10	170.0	99.2
Fill-FTD-Bank_3_HEX_36L_JRC-exp 4	20.7 821.5	19.1 61.2	-19.1	1.90	735	100.5
Fill-SMV-Bank_3_HEX_36L_JRC-exp 7	18.8 835.4	19.4 78.3	-18.7	7.85	174	98.3
Fill-FTD-Bank_3_HEX_36L_JRC-exp 6	20.9 822.4	21.2 64.2	-19.4	1.96	707	100.0
Fill-FTD-Bank_3_HEX_36L_JRC-exp 7	20.3 825.0	22.3 63.5	-19.3	2.10	663	100.4

Table 32: Main parameters values obtained during defuelling tests

Defuelling Test number	Initial SOC (%)	Initial and Final P (bar)	Initial and Final Av. T (°C)	Average MF (g/s)	Emptying time (s)
Defuelling- Ref case-exp 1	98.4	704.6 50.1	23.7 -24.6	-0.3801	3296
Defuelling- Ref case-exp 2	100.2	722.4 50.0	22.9 -25.3	-0.3682	3476
Defuelling- Init temp-exp 3	98.1	770.11 50.01	51.9 0.2	-0.3959	3194
Defuelling- Low MFR-exp 4	97.5	693.4 50.0	22.8 -15.0	-0.1833	6800

Defuelling- High MFR-exp 5	99.0	709.6 200.7	23.0 -33.2	-1.9962	398

Next figures (Figure 39 to 50) show the evolution of different parameters; inlet gas temperature (IT2), temperature of the gas on top and bottom of the tank (TT5 and TT1), Tank pressure (TP), temperature of the composite-liner interface on a hot spot on top of the tank (TC10), the temperature of the external wall (EWT3) and the mass flow (MF) during the fuelling tests. The data represented can be identified in the given drawings (Figures 35 to 37).

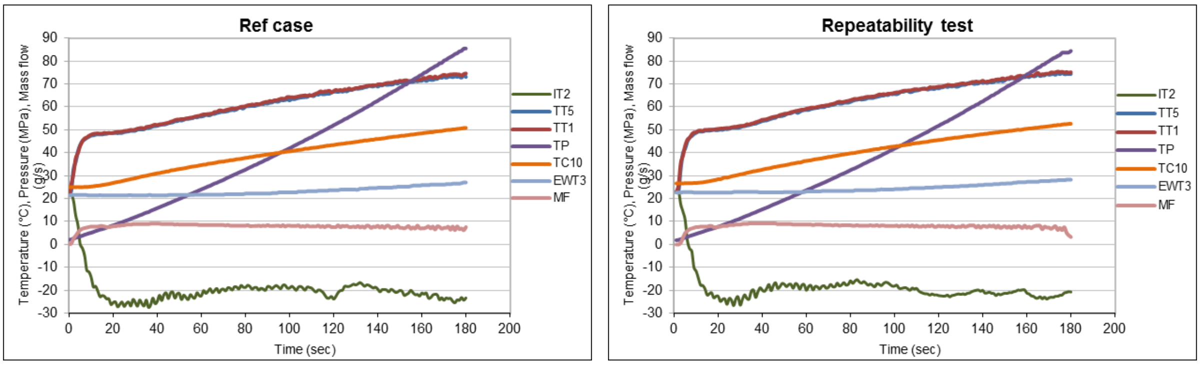


Figure 39: Fill-SMV-Bank_3_HEX_36L_JRC-exp 1 and Fill-SMV-Bank_3_HEX_36L_JRC-exp 2. Filling reference cases

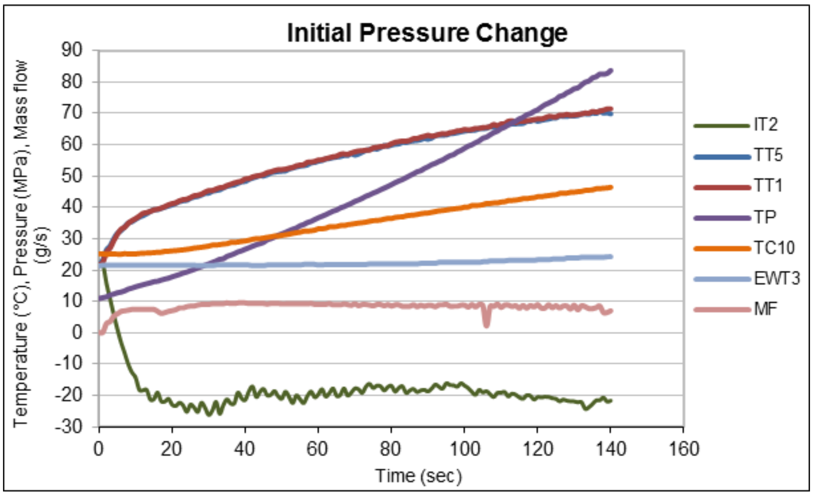


Figure 40: Fill-SMV-Bank_3_HEX_36L_JRC-exp 3. Initial pressure change

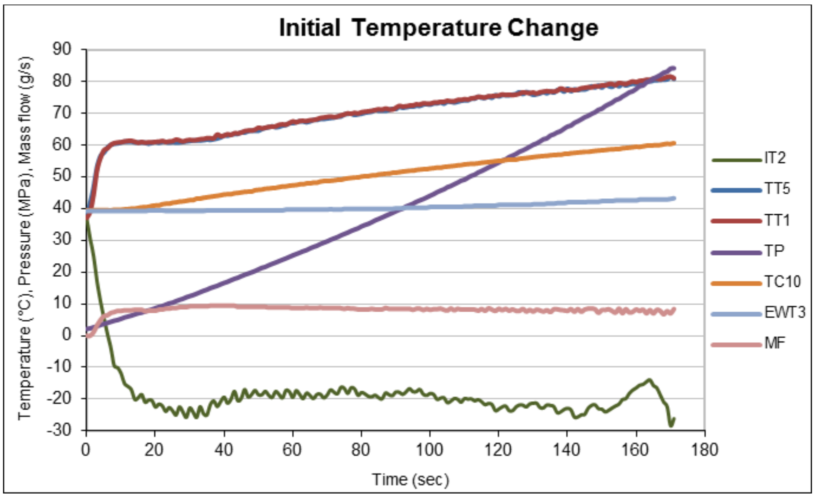


Figure 41: Fill-SMV-Bank_3_HEX_36L_JRC-exp 4. Initial temperature change

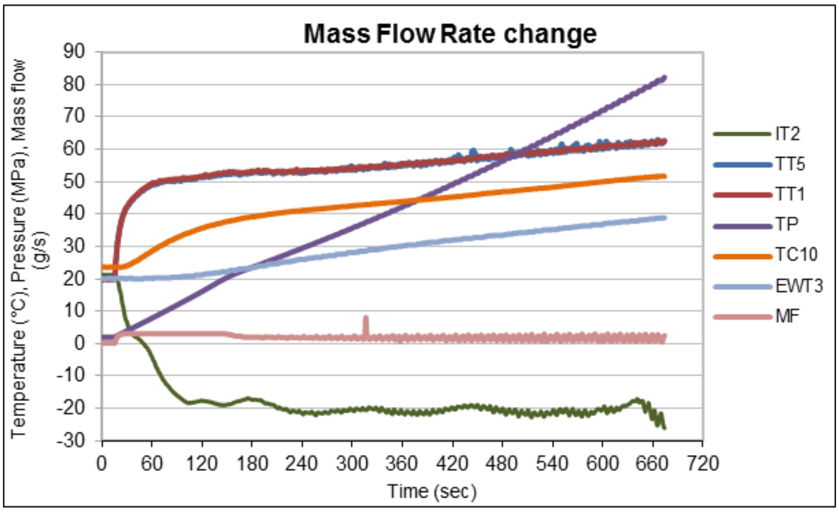


Figure 42: Fill-SMV-Bank_3_HEX_36L_JRC-exp 5. Mass flow rate change

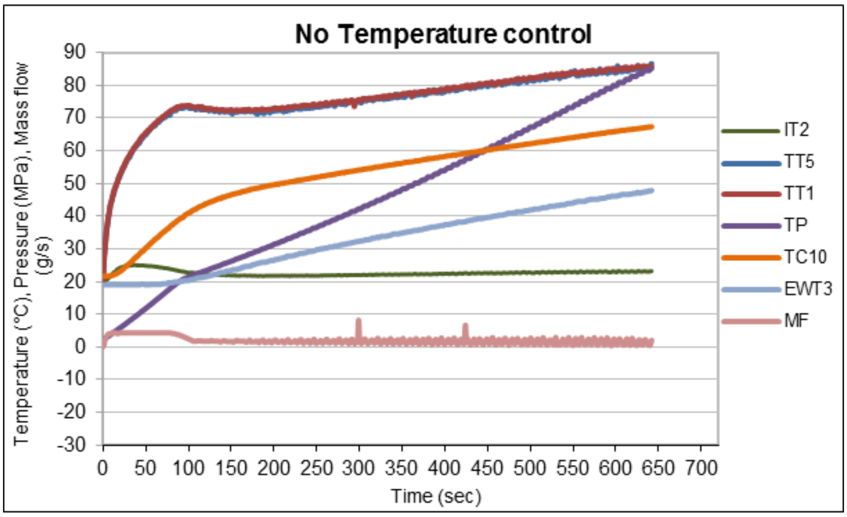


Figure 43: Fill-SMV-Bank_3_HEX_36L_JRC-exp 6. No temperature control

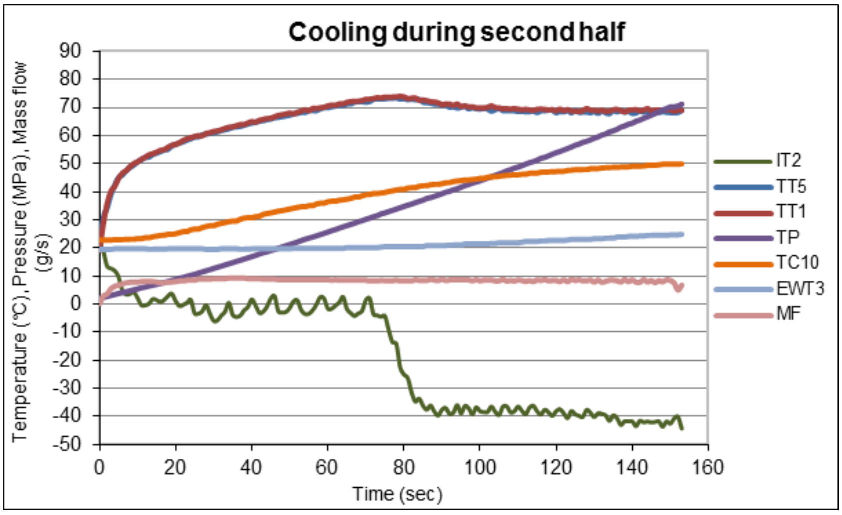


Figure 44: Fill-EB-Bank_3_HEX_36L_JRC-exp 2. Filing energy based, first part at 0°C, second part at -40°C

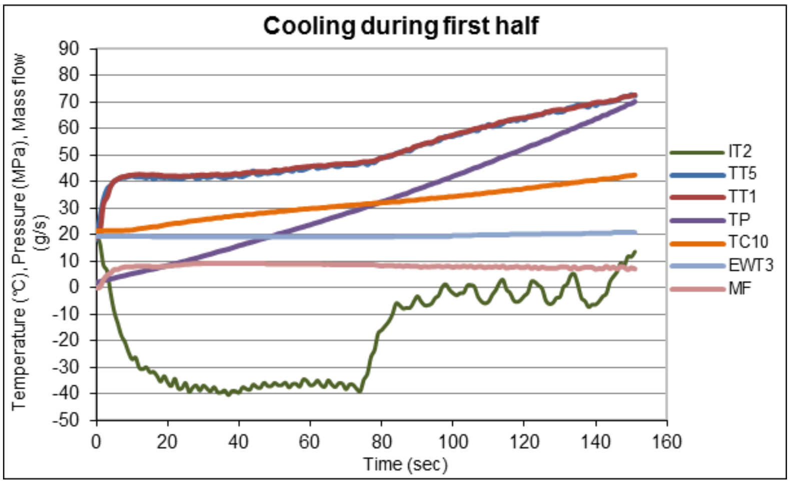


Figure 45: Fill-EB-Bank_3_HEX_36L_JRC-exp 3. Filing energy based, first part at -40°C, second part at 0°C

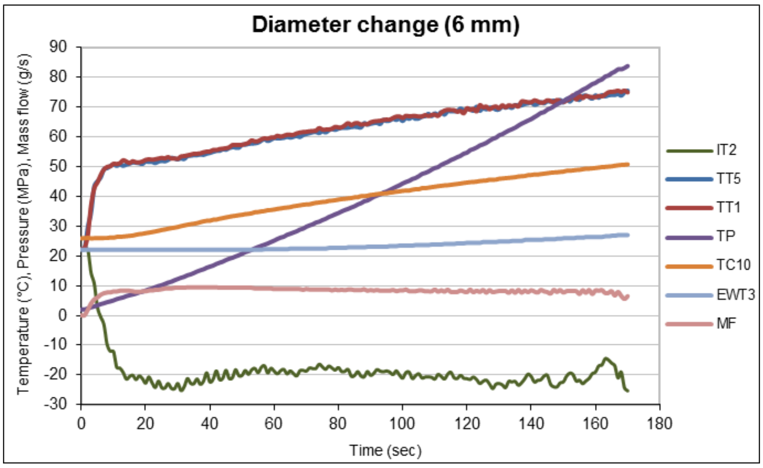


Figure 46: Fill-FTD-Bank_3_HEX_36L_JRC-exp 3. Diameter change (Inlet opening of 6 mm)

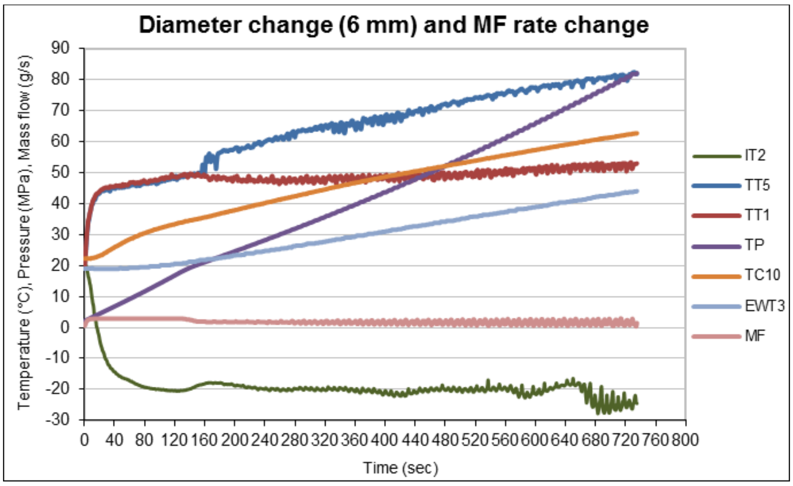


Figure 47: Fill-FTD-Bank_3_HEX_36L_JRC-exp 4. Diameter change (Inlet opening of 6 mm) and mass flow rate change.

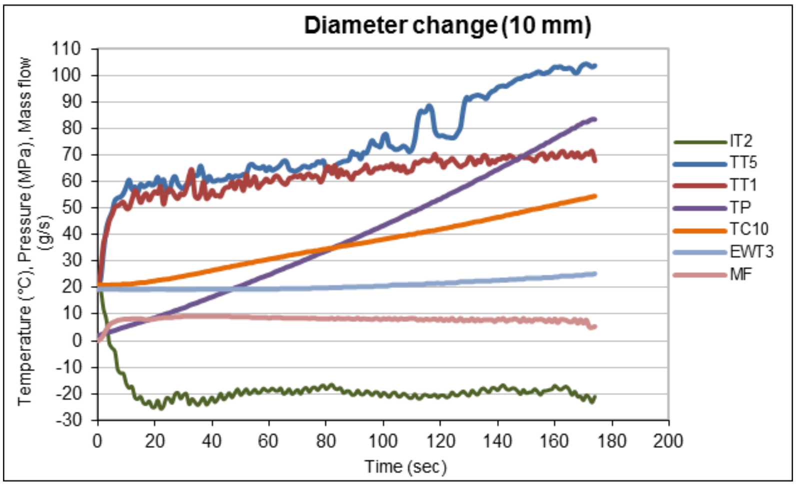


Figure 48: Fill-SMV-Bank_3_HEX_36L_JRC-exp 7. Diameter change (Inlet opening of 10 mm)

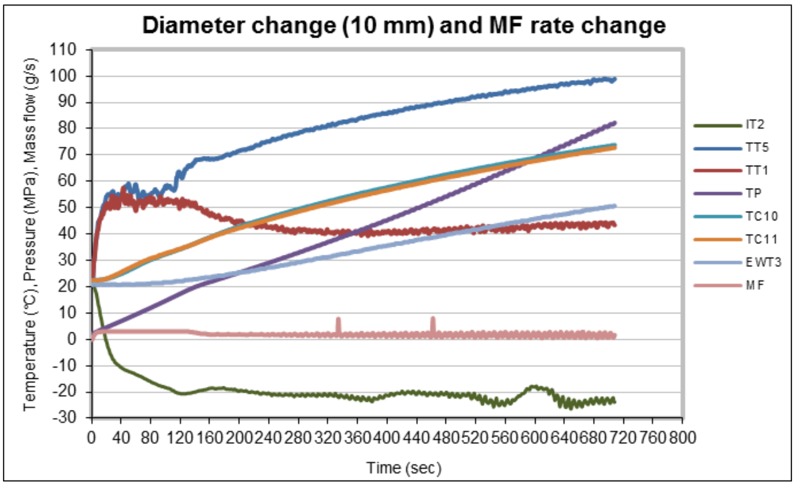


Figure 49: Fill-FTD-Bank_3_HEX_36L_JRC-exp 6. Diameter change (Inlet opening of 10 mm) and mass flow rate change.

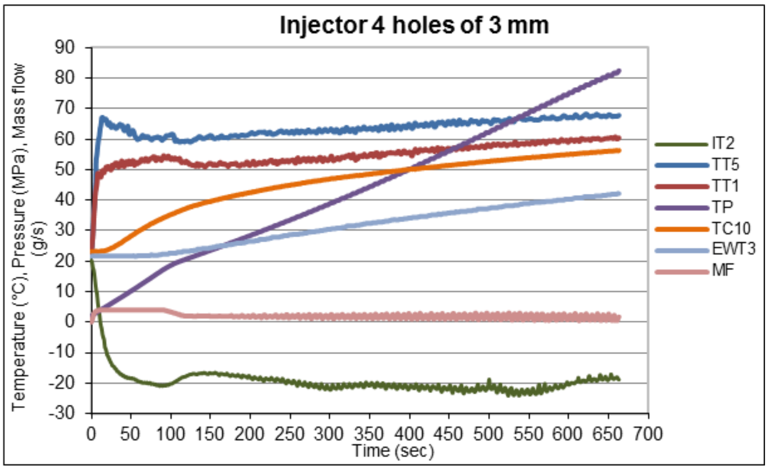


Figure 50: Fill-FTD-Bank_3_HEX_36L_JRC-exp 7. Filing with an injector with 4 holes of 3 mm diameter each

In the following figures (Figure 51 to 53) the evolution of different parameters; temperature of the gas on top and bottom of the tank (TT5 and TT1), Tank pressure (TP), temperature of the composite-liner interface on top and bottom of the tank (TC10 and TC9), the temperature of the external wall on top and bottom of the tank (EWT3 and EWT6) and the mass flow (MF) during the different defuelling cases are shown.

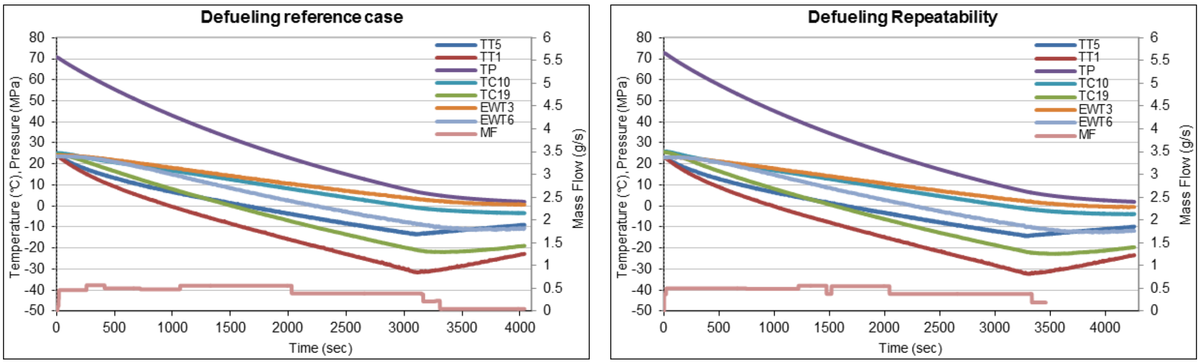


Figure 51: Defuelling- Ref case-exp 1 and Defuelling Ref case-exp 2. Defuelling reference cases.

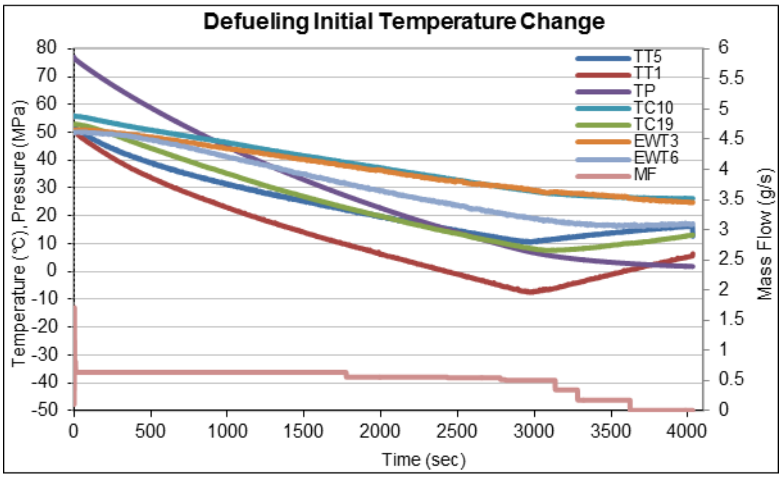


Figure 52: Defuelling- Init temp-exp 3. Defuelling starting at 50°C

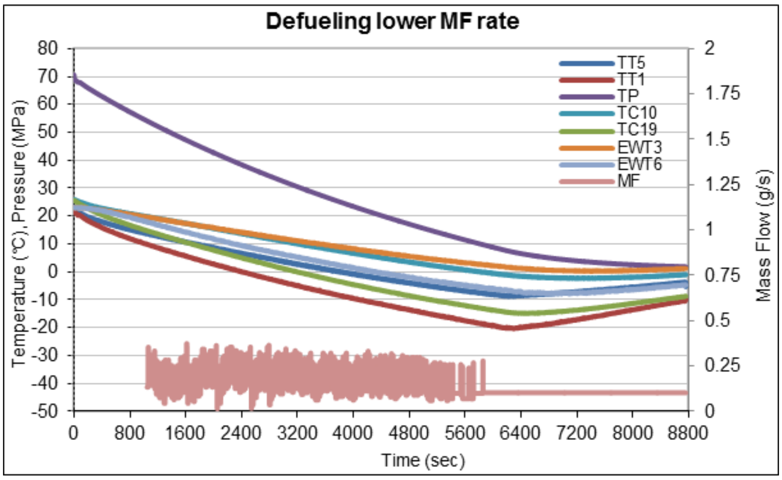


Figure 53: Defuelling- Low MFR-exp 4. Defuelling at lower mass flow rate

5.2.5 End of test and final inspection

As suggested by Hexagon, the last test was the High Mass Flow Rate defuelling (Defuelling High MFR-exp 5) so that, in case of liner buckling the continuation of the test campaign was not put in risk. In Figure 54, the evolution of different parameters measured during this test is shown.

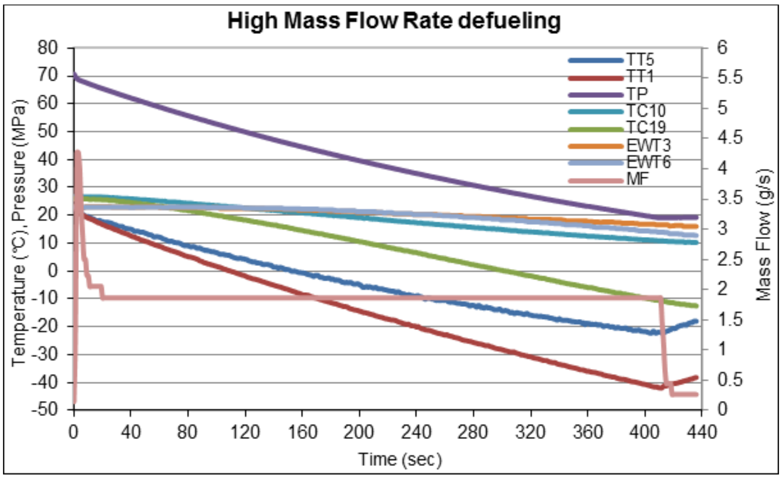


Figure 54: Defuelling- High MFR-exp 5. Defuelling down to 20 MPa at 2 g/s

Once the test campaign was finished, an inspection of the tank was done in order to identify possible tank or instrumentation damages. No damage on the tank neither on the instrumentation has been observed. However, it has been noted that one of the external thermocouples, EWT1, was displaced two centimetres (in a diagonal towards the end boss) from its original position. This could have happened in one of the injectors' changes although at this stage, we cannot determine the exact time when the thermocouple moved.

In Figure 55, a picture of the instrumented tank after HyTransfer tests is shown. In Figure 56, pictures of the two domed areas of the tank are shown. In the front dome (the one with black boss), the displacement of the thermocouple inside the aluminium tape has been pointed in red.

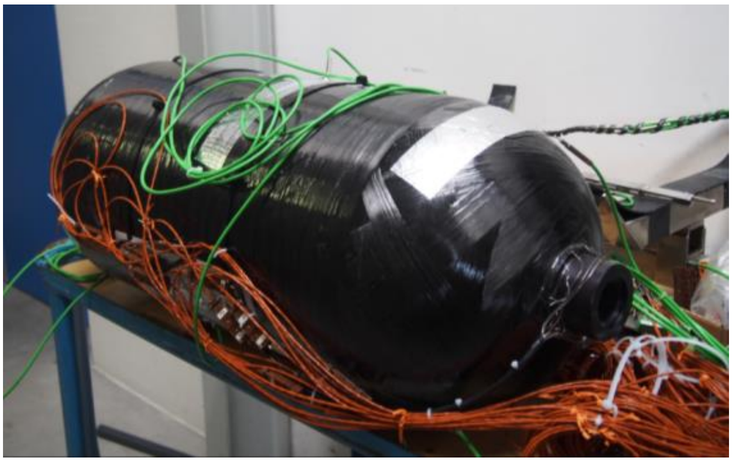


Figure 55: Instrumented Type IV tank after the test

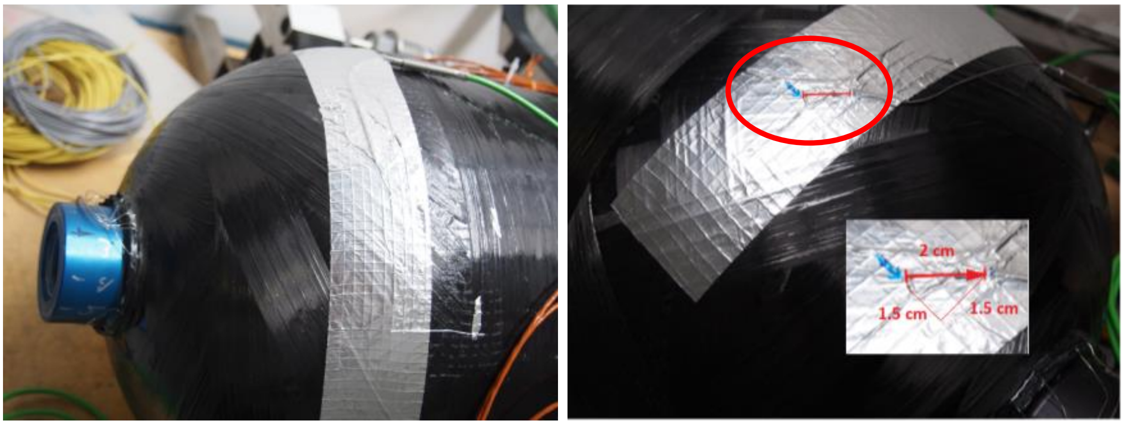


Figure 56: Detailed pictures of the two domed areas of the tank after the test with a detail of the displaced EWT 1 thermocouple

5.2.6 Operational experience

To successfully perform the 13 fillings and 5 emptyings defined in the test matrix, 54 fillings and 8 emptyings were necessary. The fillings required more tuning than the emptyings, mainly due to the difficulty to keep the pre-cooled hydrogen within the specified limits (-20 ± 3°C). This prerequisite was the one requiring most repetitions (29 fillings from the 54). Different attempts were also necessary to adjust the filling rate and to set the final pressure (to get a final SOC close to 100%).

Regarding the emptyings, a couple of trials were necessary to adjust the emptying rate to the target values.

5.2.7 Files with data recorded in GasTeF

The 18 files (corresponding to each of the experiments performed) have been divided in two folders. Most of the files, 14, are in the first group (1 of 2) and they contain all the specific data required for the HyTransfer project. The remaining 4 files (2 of 2) present some extra data recorded in GasTeF. In both folders, an explanatory Table of measurements (in order of appearance) is given.

5.3 Test campaign on Type IV short tank at AL-aT

5.3.1 Introduction

In the following section we present the tests performed with the Hexagon Lincoln 36L short cylinder. It began with the test bench installation and adjustment, as well as the sensor calibration, followed by the specified testing. Finally the recorded results will be presented.

5.3.2 Test preparation

The fuelling installation was prepared and adapted to have the upstream and flow metering instrumentation at the good location. The tank was then installed on the scale with the thermocouple tree adjusted to measure in the vertical plan, as shown on Figure 57.

Figure 57: 36L tank installation

NB: on the first positioning shown on the picture, the tank was not at the right position, the black boss should be at inlet and the thermocouple tree is vertical, when the hole for pressure measurement is vertical

The thermocouple tree, as well as the inlet plug were mounted with a specific set of O-rings and a lubricant grease. The pressure sensors are then installed on the inlet line and at the back of the tank. In addition 6 thermocouples are stick on the external wall with aluminium tape, 3 on the top (front dome, back dome and middle) and 3 at the bottom (front dome, back dome and middle). The external wall thermocouples are made of thin plate helping to have a good contact with the tank. In addition 2 thermocouples for ambient temperature measurement were installed, one in the front area of the tank and another in the back area of the tank. Each thermocouple was then tested and connected. During the tank transportation, two of the liner/composite wrapping thermocouples were broken [N°23 and 25]. Figure 58 shows the finally installed tank and Figure 59 shows the Process and Instrument Diagram of the test bench.

Figure 58: Finalized installation

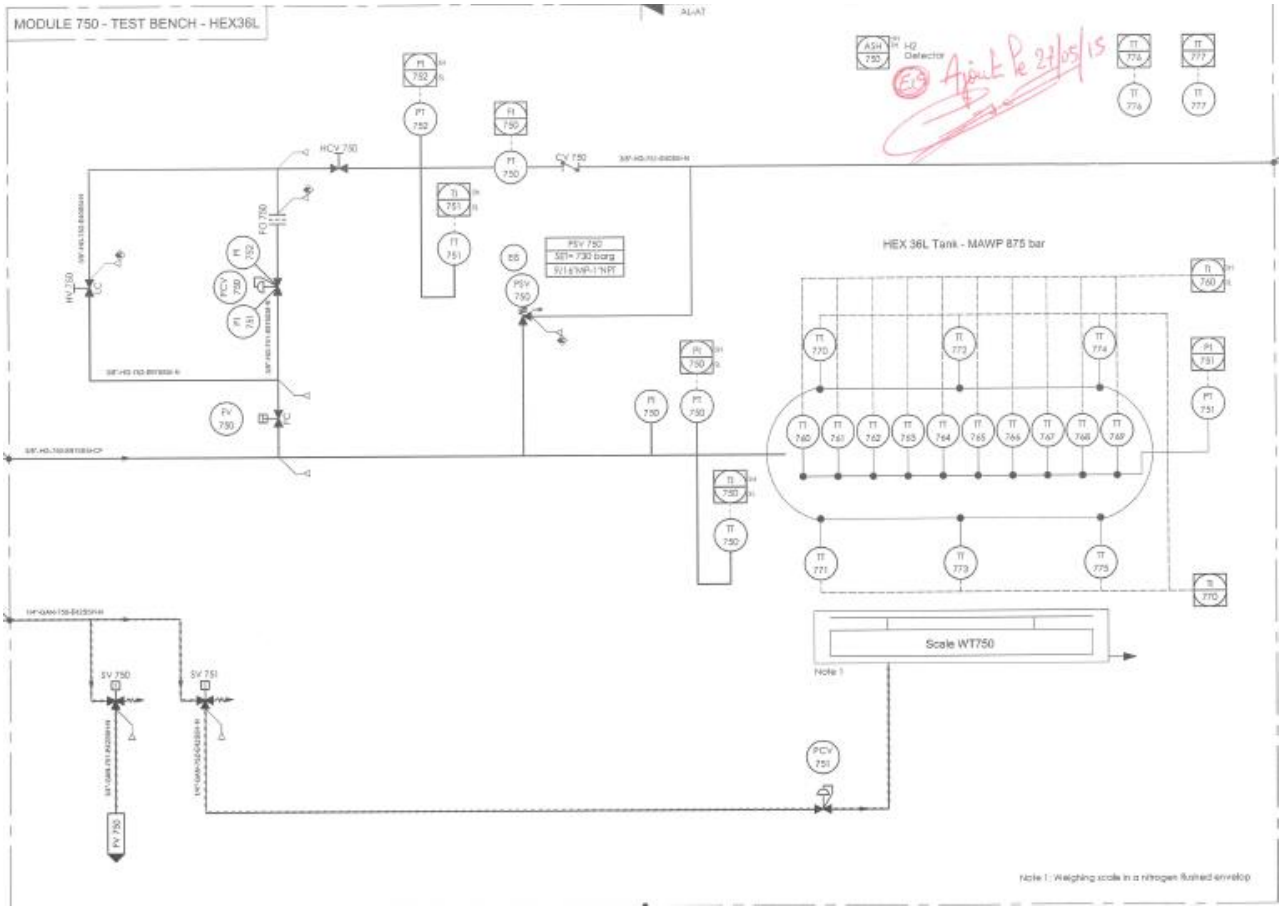


Figure 59: Installation P&ID

In Figure 60 and 61 associated with Table 33, give the detailed position of the thermocouple measurements of the tank.

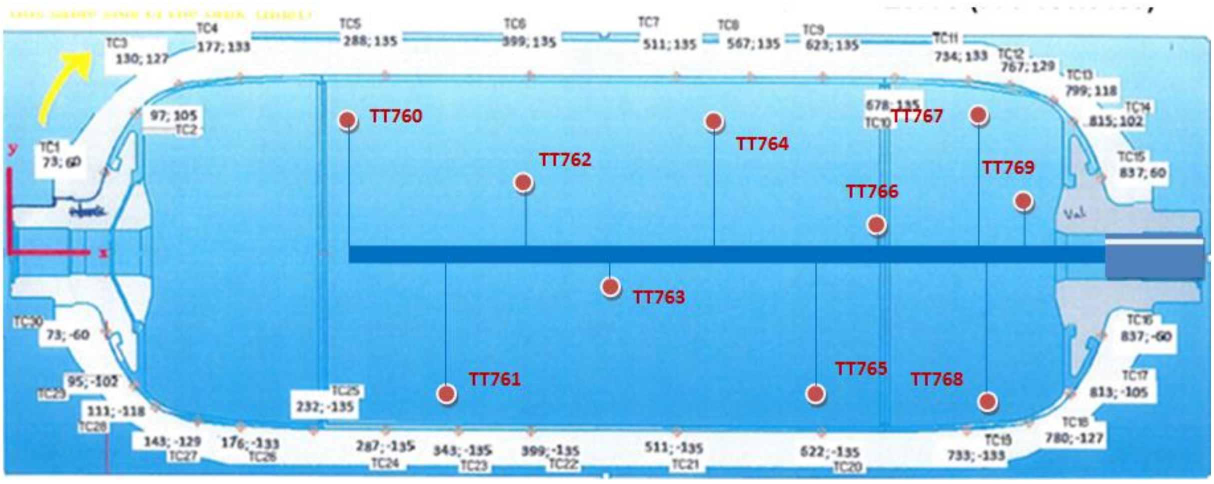


Figure 60: Position of Internal thermocouples (TT760 - TT769) and thermocouples placed between liner and wrapping (TC)

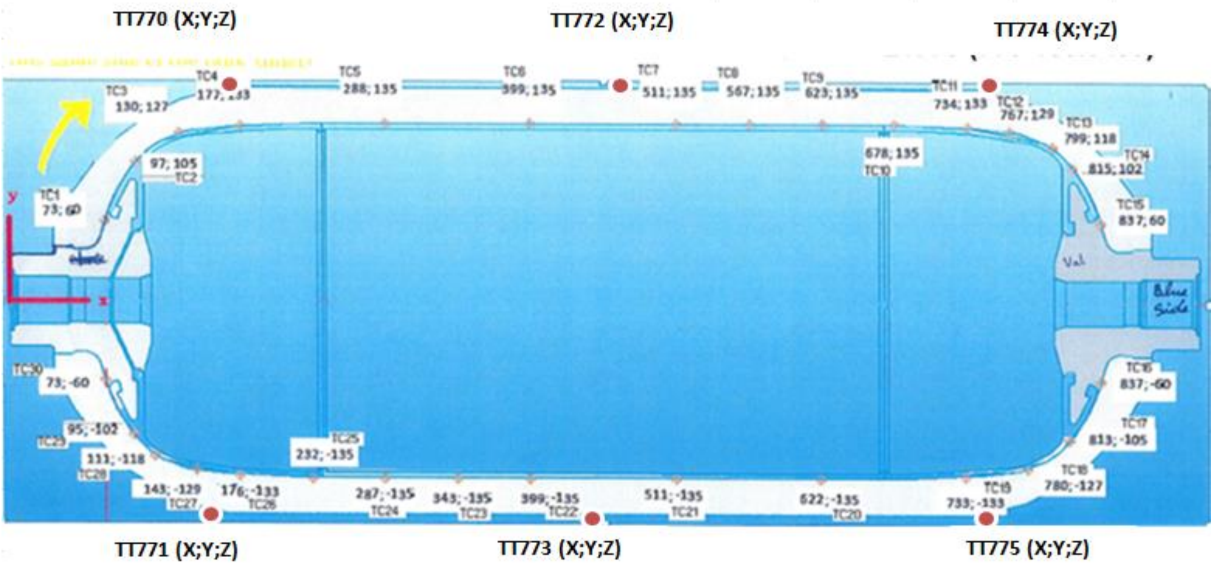


Figure 61: Position of External Thermocouples (TT770 - TT775) and thermocouples placed between liner and wrapping (TC)

Table 33: Position of the different tank thermocouples in (mm)

Thermocouple n°	x position (mm)	y position (mm)	z position (mm)
Gas temperature			
TT760	330	115	0
TT761	390	-115	0
TT762	445	60	0
TT763	505	-60	0
TT764	565	115	0
TT765	625	-115	0
TT766	700	0	20
TT767	745	115	0
TT768	745	-115	0
TT769	780	0	20
Ext wall temperature			
TT770	175	160	0
TT771	170	-160	0
TT772	440	160	-40
TT773	445	-160	-50
TT774	730	160	0
TT775	725	-160	0
Liner temperature			
TC1	73	60	0
TC2	97	105	0
TC3	130	127	0
TC4	177	133	0
TC5	288	135	0

TC6	399	135	0
TC7	511	135	0
TC8	567	135	0
TC9	623	135	0
TC10	678	135	0
TC11	734	133	0
TC12	767	129	0
TC13	799	118	0
TC14	815	102	0
TC15	837	60	0
TC16	837	-60	0
TC17	813	-105	0
TC18	780	-127	0
TC19	733	-133	0
TC20	622	-135	0
TC21	511	-135	0
TC22	399	-135	0
TC23 - broken	343	-135	0
TC24	287	-135	0
TC25 – broken	232	-135	0
TC26	176	-133	0
TC27	143	-129	0
TC28	111	-118	0
TC29	95	-102	0
TC30	73	-60	0

In addition to the thermocouples, all other elements position was identified, as shown in Figure 62, 63 and 64. Table 34 gives the position of the equipments on lines.

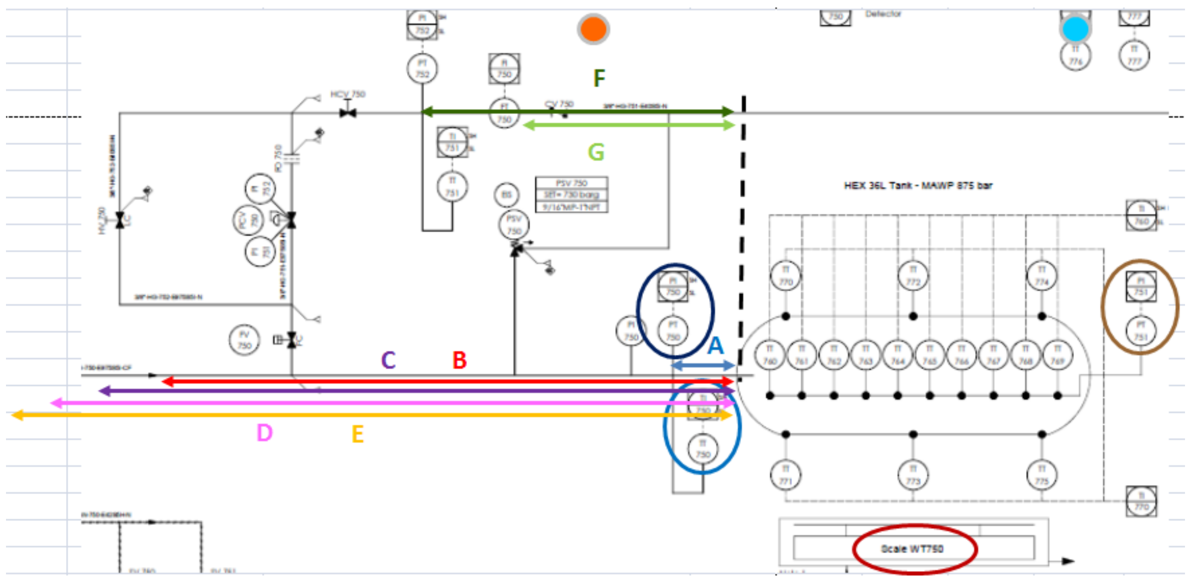


Figure 62: Position of the pressure, auxiliary temperature and mass flow meter measurement points

Figure 63: Picture of the equipment positions – Part 1

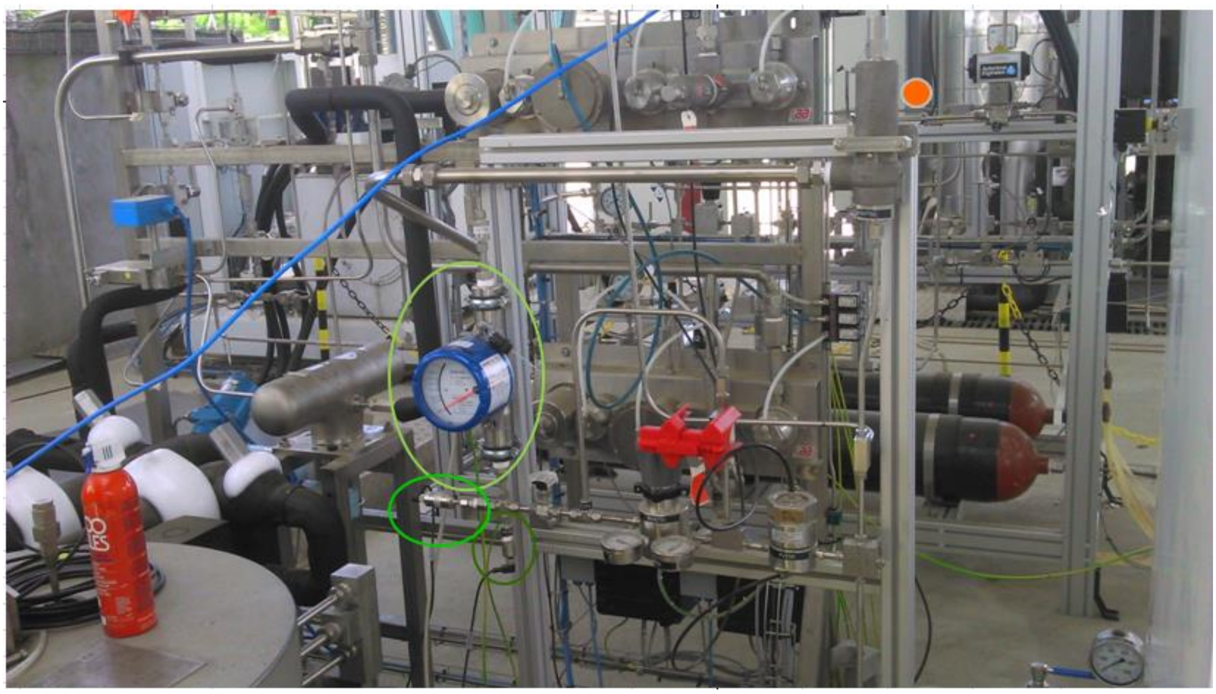


Figure 64: Picture of the equipment positions – Part 2

Table 34: Equipment positions details

Pressure	Approximative value of pipe length	
PT450	C = 475 cm	from the inlet of the tank (0 of the axis)
PT750	A = 10 cm	from the inlet of the tank (0 of the axis)
PT751	Rear of the tank, on the thermocouple tree plug	
PT752	F = 225 cm	from the inlet of the tank (0 of the axis)

Temperature	Approximative value of pipe length			
TT450	B = 415 cm	from the inlet of the tank (0 of the axis)		
TT750	A = 10 cm	from the inlet of the tank (0 of the axis)		
TT751	F = 225 cm	from the inlet of the tank (0 of the axis)		
TT776	X = -70 cm	Y = 120 cm	Z = -60cm	(same axis than the bottle)
TT777	X = 90 cm	Y = 190 cm	Z = -70 cm	(same axis than the bottle)

Mass	Approximative value of pipe length	
WT750	Under the tank	
FT450	E = 690 cm	from the inlet of the tank (0 of the axis)
FT451	D = 615 cm	from the inlet of the tank (0 of the axis)
FT750	G = 240 cm	from the inlet of the tank (0 of the axis)

Once all sensors were properly connected and identified, different step of calibration actions were performed. The scale was delivered with a calibration certificate and additional verification were performed with calibrated masses at different positions on the tank. It is noticed that the wind of the environment is generating an error noise of about 20g as shown in Table 35.

Table 35: Calibration results of scale

Mass	Measurement point 1	Measurement point 2	Measurement point 3	Measurement point 4
1 kg	0,970 kg	1,020 kg	0,990 kg	0,990 kg
2 kg	2,010 kg	1,970 kg	X	X
0 kg	0 to 20g error	X	X	X

For the thermocouples, they were all compared to a calibrated device Beamex MC2 614-0038 CVN°: 07E140660. They were all in the range of +/- 1°C error of Type T and +/- 2°C of Type K thermocouples errors, except TC05 which had high fluctuations. The 2 PT100 sensors used were compared to ambient and factory calibration was taken as reference.

For the pressure sensors (excepted the defuelling line flowmeter correction sensor), in addition to the factory calibration certificates, a calibration was performed with a calibrated pressure sensor during the pressure testing under nitrogen as shown in Table 36:

Table 36: Calibration results of pressure sensors

	Ref PT	PT450	Ref PT	PT750	Ref PT	PT751
Measurement point 1	0 bar	1,2 bar	0 bar	0,7 bar	0 bar	1,1 bar
Measurement point 2	196,6 bar	196,3 bar	196,8 bar	195,9 bar	196,8 bar	196,8 bar
Measurement point 3	382,0 bar	379,0 bar	382, 0 bar	378,2 bar	382,0 bar	381,8 bar
Measurement point 4	627,2 bar	625,0 bar	622,0 bar	623,0 bar	622,0 bar	623,4 bar

Nota: it appeared during the testing that PT750 shifted during some experiments, which needed re-adjustment.

The calibration of equipments was followed by a check of all safety functionalities including safety switches and fire protections. The installation was then purged with hydrogen and leak checked.

During hydrogen defuelling of these first tests, the flow orifice and the needle valve on the defuelling line were tested and adjusted to reach the different defuelling flow rates as specified in the test matrix. Additionally some pre-cooling pre-testing and fuelling pressure ramp adjustments were also performed to comply with the test matrix. The pre-cooling tests helped to define the appropriate pre-cooling temperature associated to the heat exchanger and to define a strategy of pre-cooling of the lines before each test.

A first test was performed on April 30th 2015, that led to a strong leak at the thermocouple tree, due to an inappropriate sizing of the O-ring and the plug. The single O-ring was replaced by an O-ring with back-up ring. An internal visual inspection was carried out to look for possible liner buckling. The test installation was prepared again for testing and the test campaign could be resumed at the beginning of June.

5.3.3 AL-aT test matrix

The test performed at AL-aT were taken out the test matrix presented in previous sections and rearranged to limit the number of cylinder opening and installation modification. The 12 fuelling tests + 3 extra tests and the 7 specified defuellings + 8 not-specified are presented in the following Table 37 and 38:

Table 37: Test matrix in fuelling tests

Fuelling HEX 36 L	Injector diameter	Initial P	Initial T	Inlet gas T	Av. MF	End of fill criterion	Data file name
No injector High flow	10mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 7

No injector Low flow	10mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_2_HEX_36L_ALAT-exp 6
Reference case	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 1
Repeatability	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 2
Mass flow rate change	3mm	20 barg	No conditionning	-20°C	2g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 5
Defuelling with 3 pressure steps	3mm	20 barg	No conditionning	-20°C	8 g/s by step	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 8
Initial pressure change	3mm	100 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 3
No cooling + reduced flow	3mm	20 barg	No conditionning	No cooling	2 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 6
Lower pre-cooling	3mm	20 barg	No conditionning	-40°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_2_HEX_36L_ALAT-exp 4
Larger injection Ø	6mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_2_HEX_36L_ALAT-exp 3
Mass flow rate change + Ø	6mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_2_HEX_36L_ALAT-exp 4
Radial injection	4 x 3mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_2_HEX_36L_ALAT-exp 7
High flow 1	4 x 3mm	20 barg	No conditionning	-30°C	10 g/s	SOC=100% or Tgas>85 °C	Fill-HF-Bank_2_HEX_36L_ALAT-exp 1
High flow 2	4 x 3mm	20 barg	No conditionning	-30°C	20 g/s	SOC=100% or Tgas>85 °C	Fill-HF-Bank_2_HEX_36L_ALAT-exp 2
High flow 3	4 x 3mm	20 barg	No conditionning	-30°C	30 g/s	SOC=100% or Tgas>85 °C	Fill-HF-Bank_2_HEX_36L_ALAT-exp 3

Table 38: Test matrix in defuelling tests

Defuelling HEX 36 L	Injector diameter	Initial SOC	Initial T	Av. MF	End of fill criterion	Data file name
No injector	10mm	100%	No conditionning	Constant 0.376g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 5
Reference case	3mm	100%	No conditionning	Constant 0.376 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 1
Repeatability	3mm	100%	No conditionning	Constant 0.376 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 2
Lower mass flow rate	3mm	100%	No conditionning	Constant 0.125 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 6
Lower initial SOC	3mm	80%	No conditionning	Constant 0.376 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 4
Higher mass flow rate	3mm	100%	No conditionning	Constant 2 g/s	P < 200 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 7
Ramp change	3mm	100%	No conditionning	1,5 g/s for 500s then 0,2 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_2_HEX_36L_ALAT-exp 3

5.3.4 Test results

The testings lasted one month, from the 9th of June to the 9th July 2015. In the next section, we present the results of each test day per day, with the testing conditions and various parameters. The table from 39 to 69 and the graphs from 65 to 94 give the details of the testing environment and the raw results.

5.3.4.1 Fill SMV n°7 + Defuelling n°5

Table 39: Fill SMV n°7 details

Date	9th June
Morning – Fill SMV n°7	10:07 – 10:15
Weather	Almost no wind / ~20°C ambient
Stabilization duration	3 h 45 min

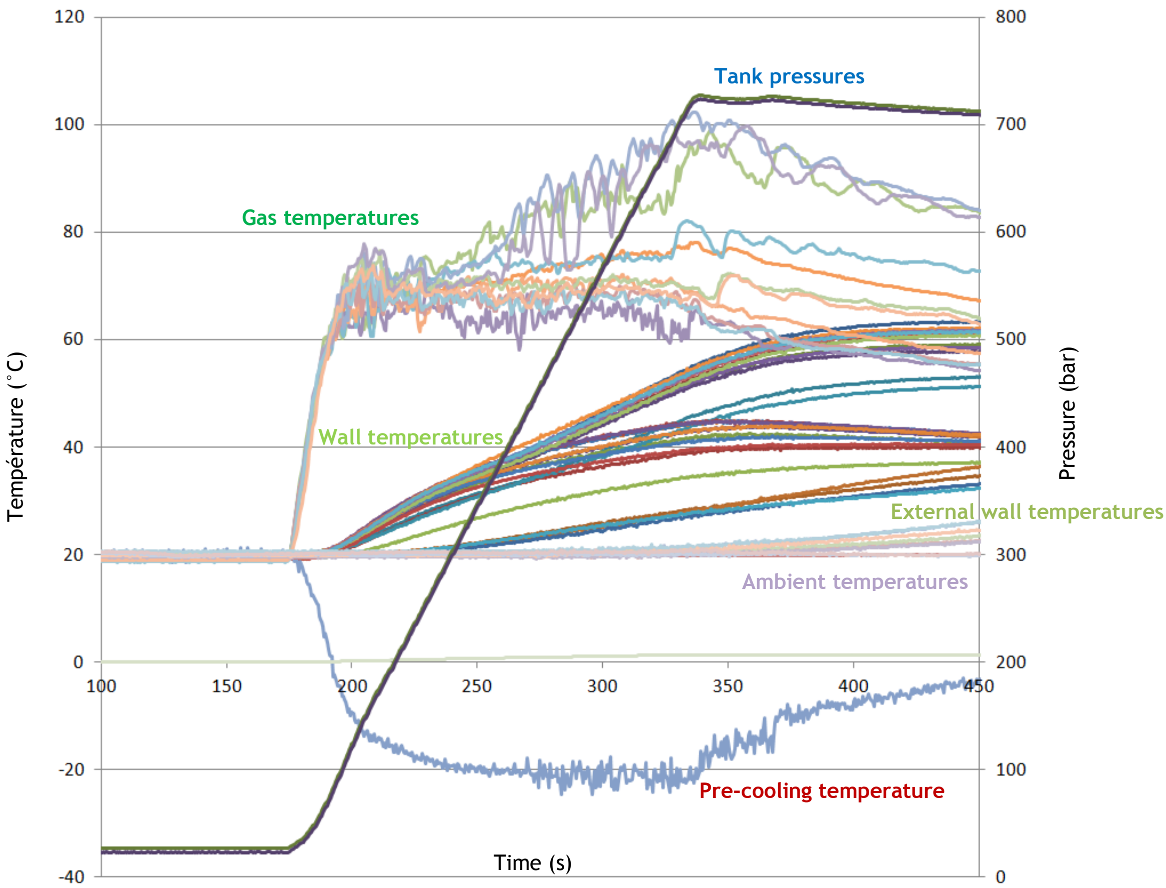


Figure 65: Fill SMV n°7 – 10mm injection Ø

Comments: pressure transmitter PT750 was 3 bar higher than PT751 at the beginning. The fuelling ramp rate was around 4,4 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -20°C. We can clearly see the temperature difference between the gas, the liner/composite wall and the external wall. At some point we see the effects of temperature stratification.

Table 40: Defuelling n°5 details

Date	9th June
Afternoon – Defuelling n°5	14:07 – 14:57
Weather	North wind / cloudy / ~22°C ambient
Stabilization duration	2 h 55 min recorded + night

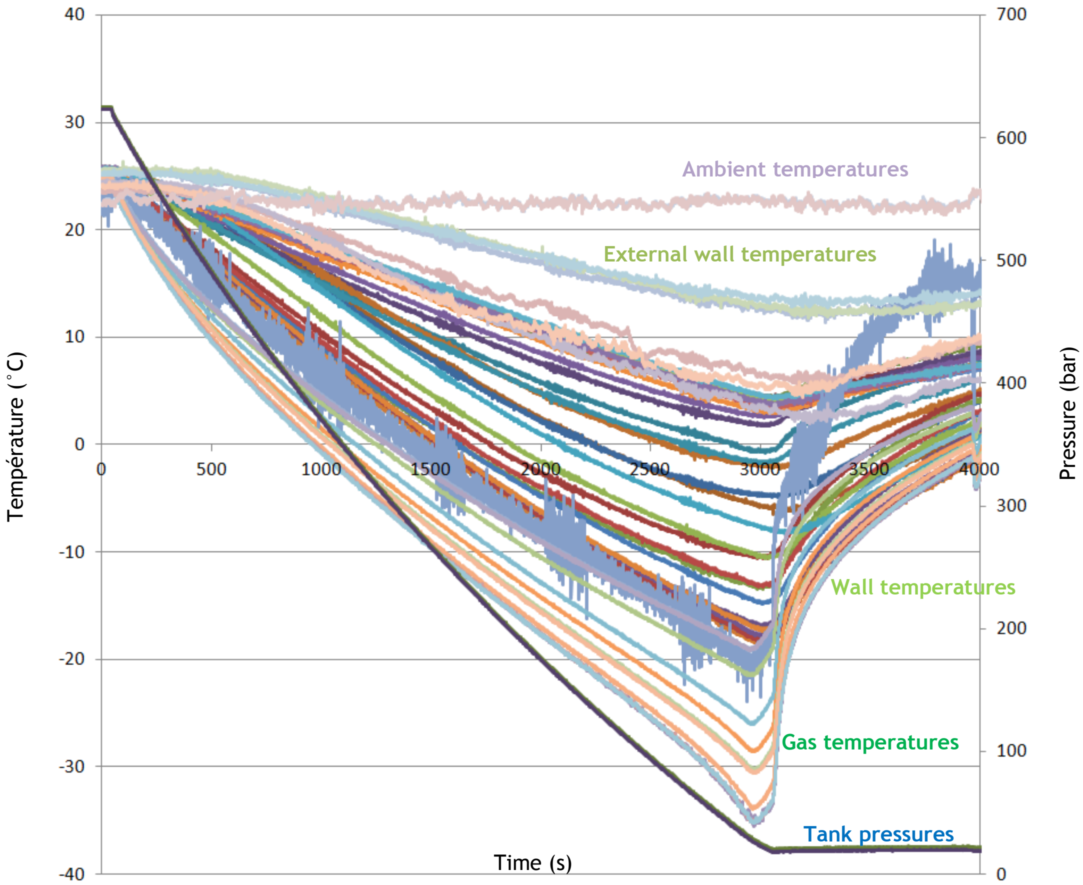


Figure 66: Defuelling n°5 – 10mm injection Ø

Comments: the defuelling started with an ambient / gas average temperature difference of ~ 2°C. The recording was stopped when this difference was less than 1°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

5.3.4.2 Fill FTD n°6+ Defuelling n°5 bis

Table 41: Fill FTD n°6 details

Date	10th June
Morning – Fill FTD n°6	08:33 – 08:51
Weather	South wind / ~19°C ambient
Stabilization duration	3 h 55 min

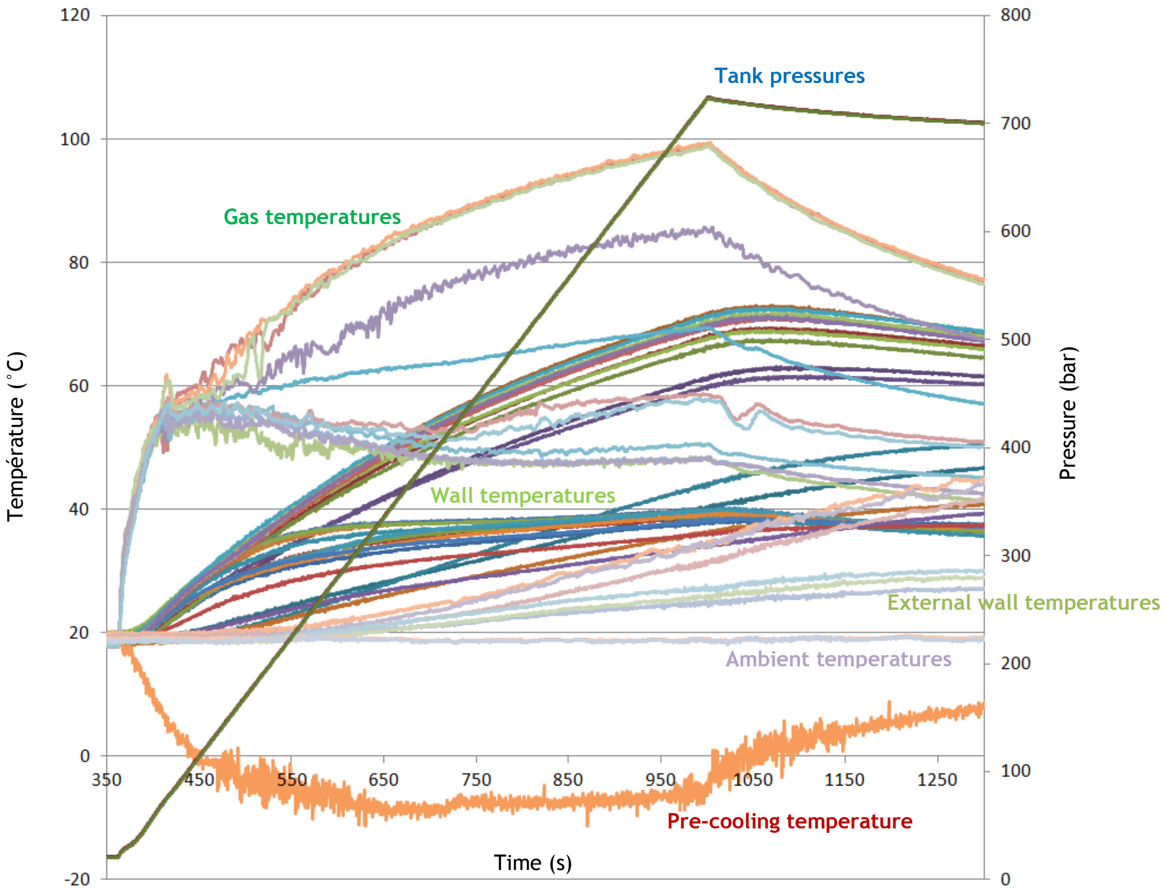


Figure 67: Fill FTD n°6 – 10mm injection Ø + low flow rate

Comments: Due to lower flow rate the pre-cooling reaches -8°C minimum. The fuelling ramp rate was around 1,1 bar/s and the fuelling was stopped on a pressure condition. We can see the temperature difference between the gas, the liner/composite wall and the external wall. The stratification effect is longer as the fuelling is longer.

Table 42: Defuelling n°5 bis details

Date	10^{th} June
Afternoon – Defuelling n°5 bis	12:45 – 13:40
Weather	South wind / cloudy / ~20°C ambient
Stabilization duration	3 h 15 min recorded + night

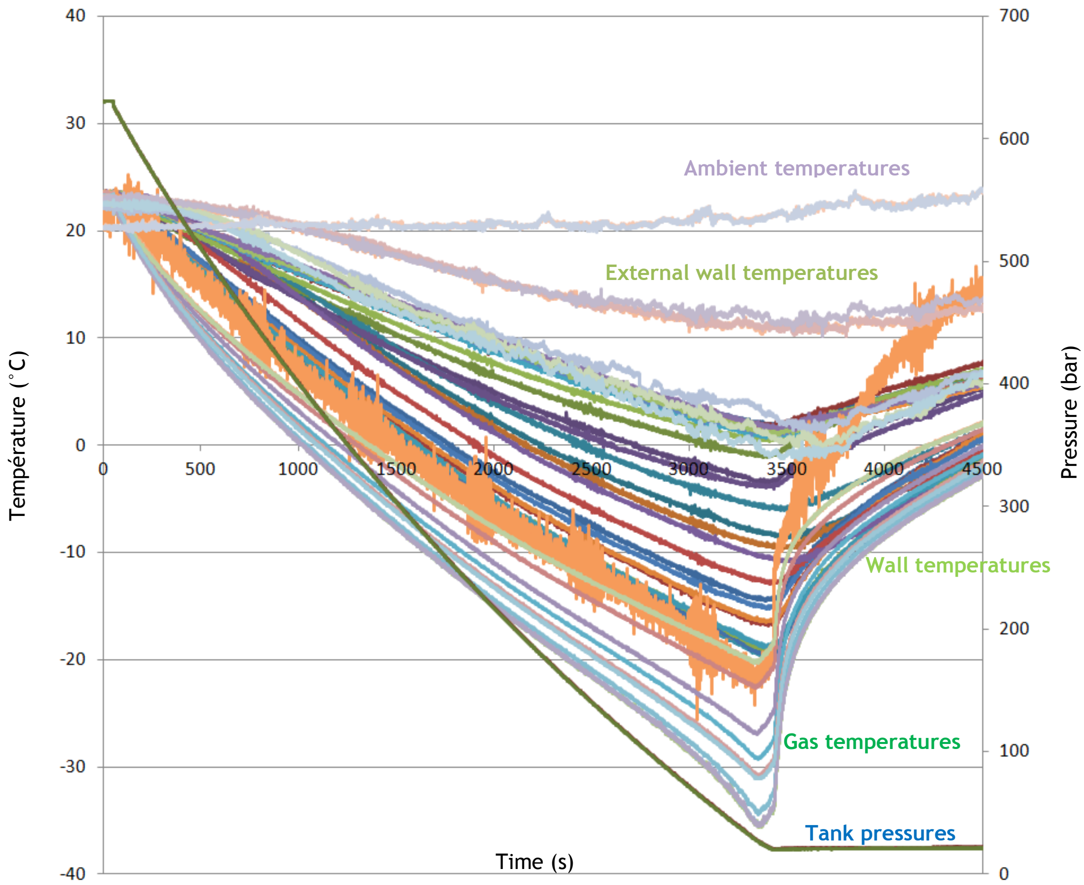


Figure 68: Defuelling n°5 bis – 10mm injection Ø

Comments: the defuelling started with an ambient / gas average temperature difference of ~ 3°C. The recording was stopped when this difference was less than 2°C. This is a reproduction of previous test, as there was only one defuelling specified for this injection diameter. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

The reproducibility with previous test is good, same behaviours and similar final values. Following this test, the tank was completely defuelled, purged with nitrogen. After that the 3mm injector was installed and the tank prepared at 20 bar for the next day.

5.3.4.3 Fill SMV n°1+ Defuelling n°1

Table 43: Fill SMV n°1 details

Date	11th June
Morning – Fill SMV n°1	09:08 – 09:11
Weather	Strong south wind / ~20°C ambient / Sun on the front of the tank
Stabilization duration	3 h 50 min

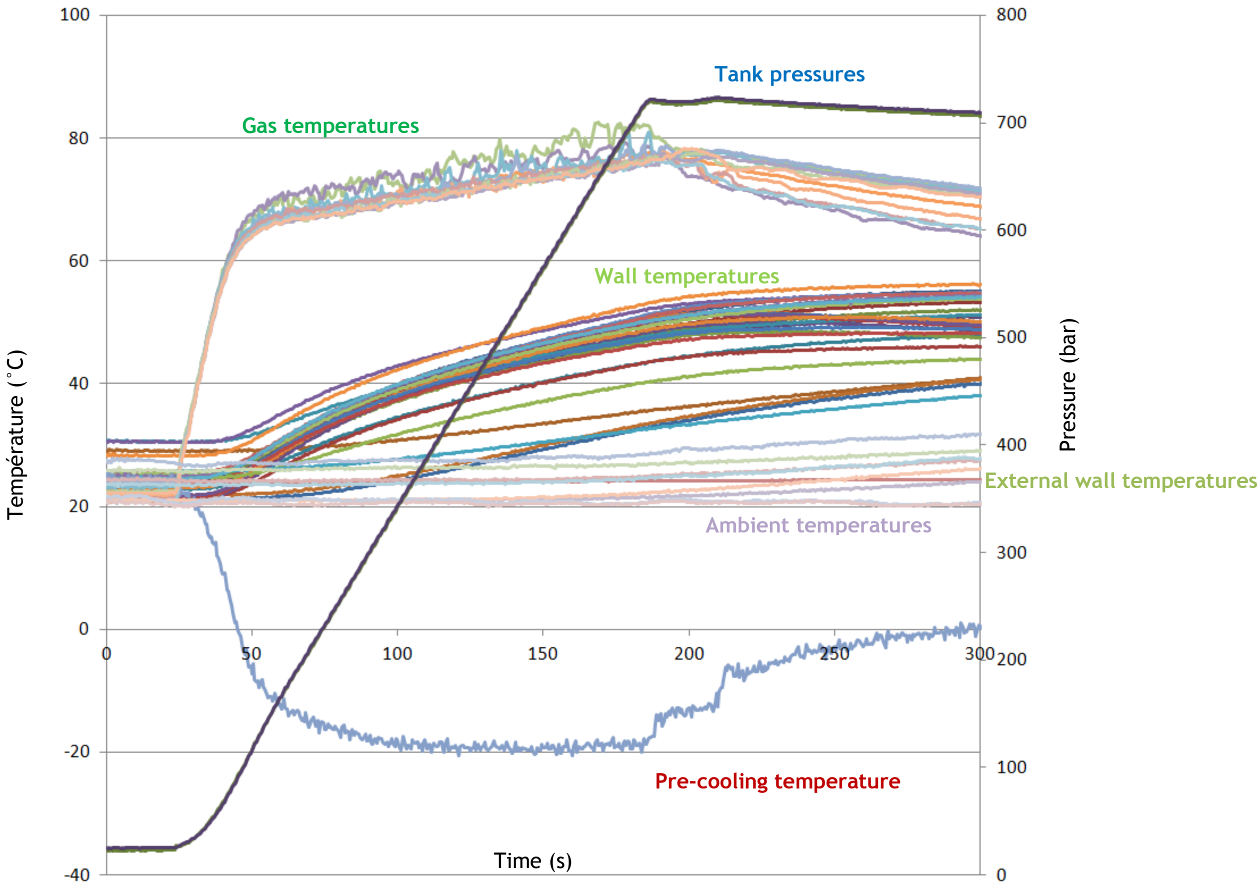


Figure 69: Fill SMV n°1 – reference case

Comments: this is the reference case with an average flow rate of 8 g/s, a pre-cooling at -20°C, no conditioning, 3mm injection diameter and an initial pressure of 20 bar. The fuelling ramp rate was around 4,4 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -20°C. In this case we observe no temperature stratification and thus the gas, wall and external wall temperatures stay separated.

Table 44: Defuelling n°1 details

Date	11th June
Afternoon – Defuelling n°1	13:10 – 14:10
Weather	Almost no wind / ~27°C ambient
Stabilization duration	3 h 30 min recorded + night

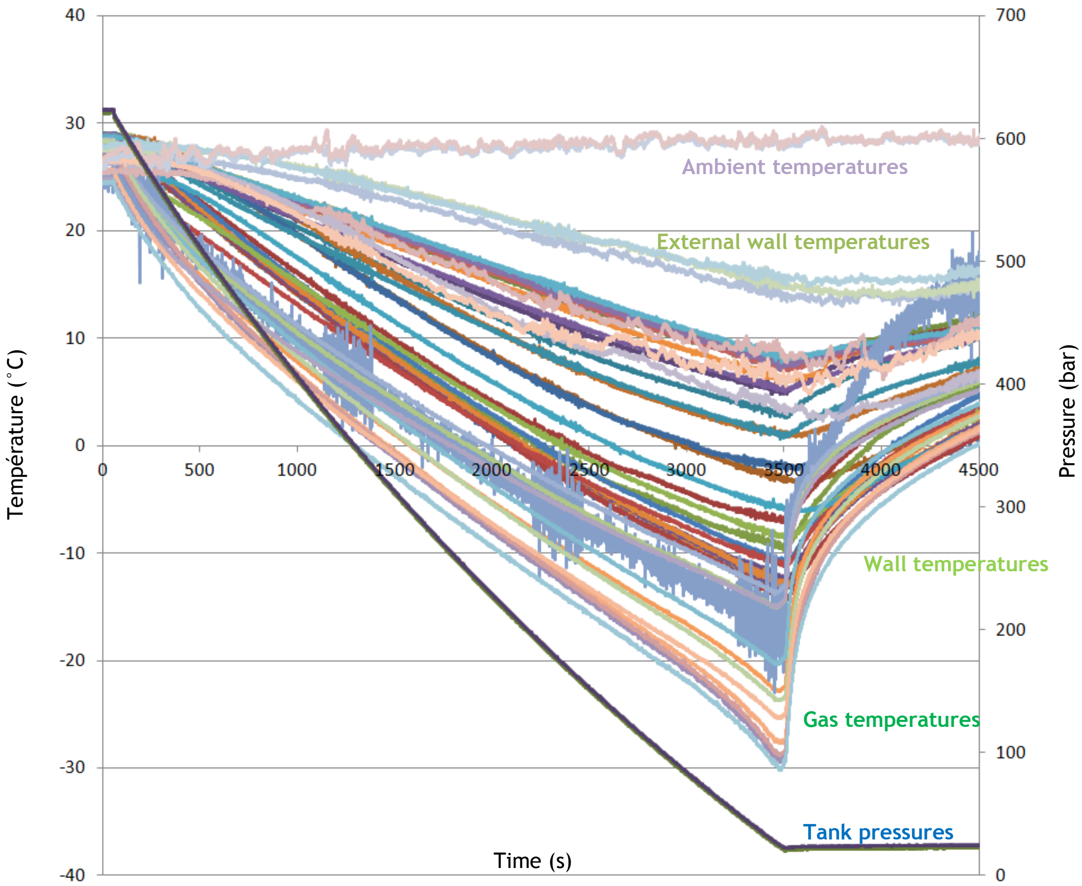


Figure 70: Defuelling n°1 – reference case

Comments: this is the reference case with a defuelling flow rate of 0,376 g/s, 3mm injection diameter, no conditioning, an initial SOC around 100%. The defuelling started with an ambient / gas average temperature difference of ~ 0°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. A first analysis shows no impact of the injection diameters. The temperature shift compared to the 10 mm injection diameter corresponds to the ambient temperature difference.

5.3.4.4 Fill SMV n°2+ Defuelling n°2

Table 45: Fill SMV n°2 details

Date	23rd June
Morning – Fill SMV n°2	09:00 – 09:05
Weather	Strong north wind / ~18°C ambient
Stabilization duration	4 h 10 min

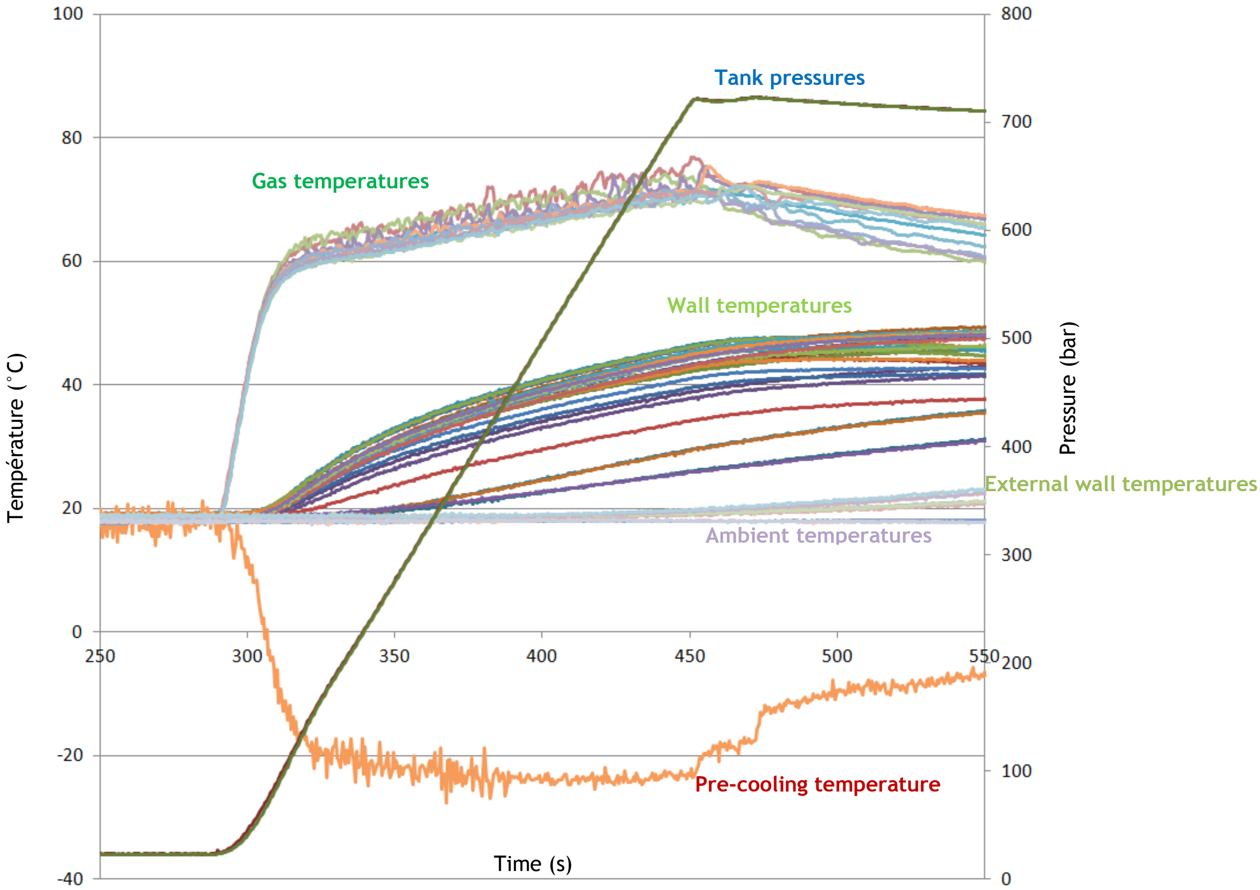


Figure 71: Fill SMV n°2 – repeatability

Comments: this is the repeatability case of the reference case. The fuelling ramp rate was around 4,4 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -22°C. In this case we observe no temperature stratification and thus the gas, wall and external wall temperatures stay separated. A comparison with the references shows about 5°C lower temperatures, which probably come from a combination of slightly lower ambient and pre-cooling temperatures.

Table 46: Defuelling n°2 details

Date	23rd June
Afternoon – Defuelling n°2	13:20 – 14:20
Weather	Strong north wind / ~20°C ambient
Stabilization duration	2 h 50 min recorded + night

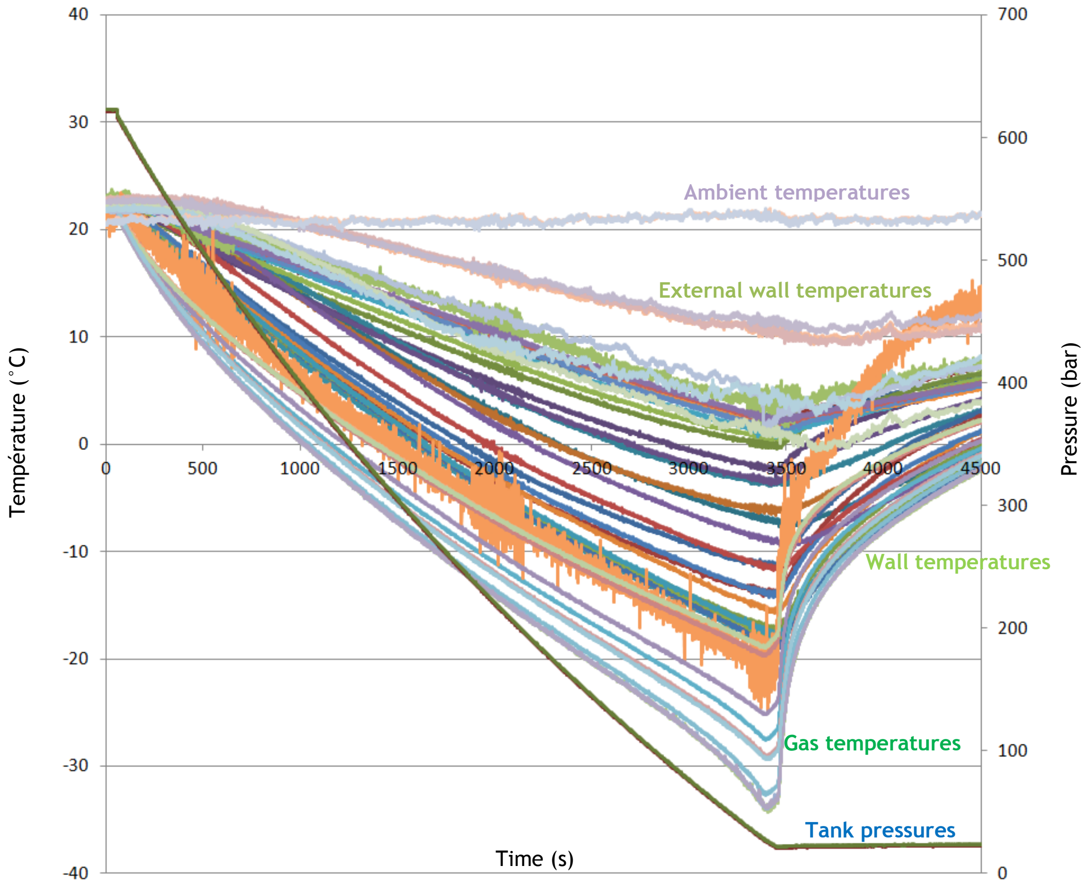


Figure 72: Defuelling n°2 – repetability

Comments: this is the repeatability case of the reference case. The defuelling started with an ambient / gas average temperature difference of ~ 2°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. Compared with the previous defuellings, the repeatability is good, global behaviour and final values.

5.3.4.5 Fill SMV n°5+ Defuelling n°6

Table 47: Fill SMV n°5 details

Date	24th June
Morning – Fill SMV n°5	08:54 – 09:00
Weather	No wind / Some sun in front of the tank / ~17°C ambient
Stabilization duration	4 h 05 min

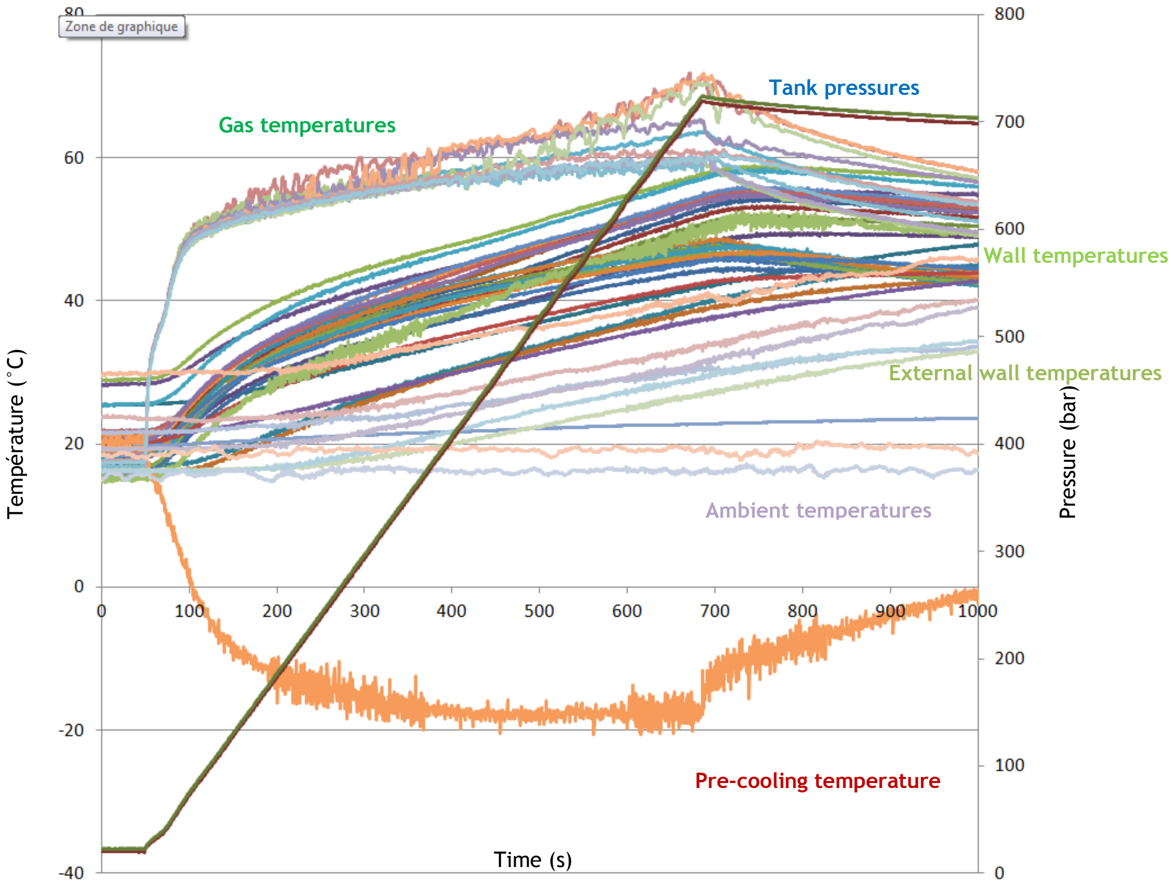


Figure 73: Fill SMV n°5 – reduced flow rate

Comments: in this test the flow rate is reduced to a lower flowrate. The fuelling ramp rate was around 1,1 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -17°C. In this case we observe again temperature stratification, but in a reduced magnitude compared with the fuelling with 10mm injection diameter.

Table 48: Defuelling n°6 details

Date	24th June
Afternoon – Defuelling n°6	13:15 – 14:20
Weather	No wind / ~20°C ambient
Stabilization duration	All night

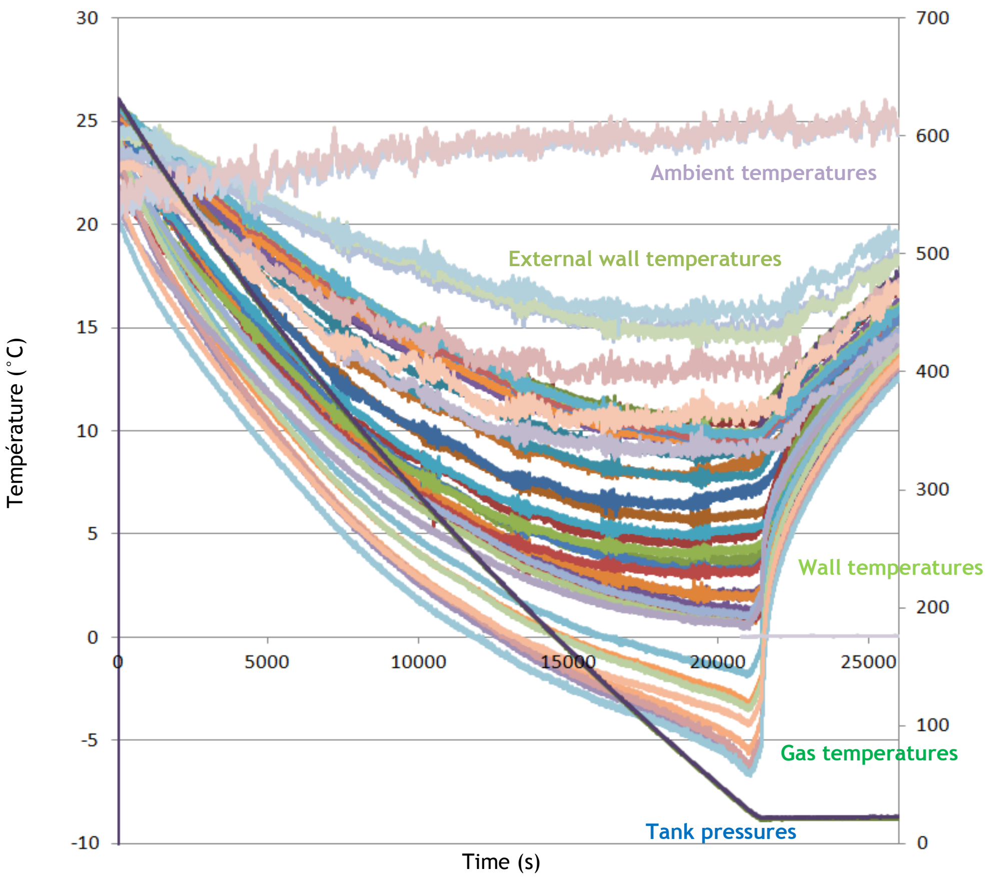


Figure 74: Defuelling n°6 – reduced defuelling flowrate

Comments: this test is performed with a lower flowrate. The defuelling started with an ambient / gas average temperature difference of ~ 2,5°C. The recording was stopped when this difference was less than 0°C, recorded all night. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. In this case we can observe the stratification established over a longer time and final temperature higher than for faster defuellings.

5.3.4.6 Fill SMV n°8+ Defuelling n°4

Table 49: Fill SMV n°8 details

Date	25th June
Morning – Fill SMV n°8	In 4 steps 08:38 – 09:10
Weather	Slight south wind / Sun in front of the tank / ~18°C ambient
Stabilization duration	3 h 35 min

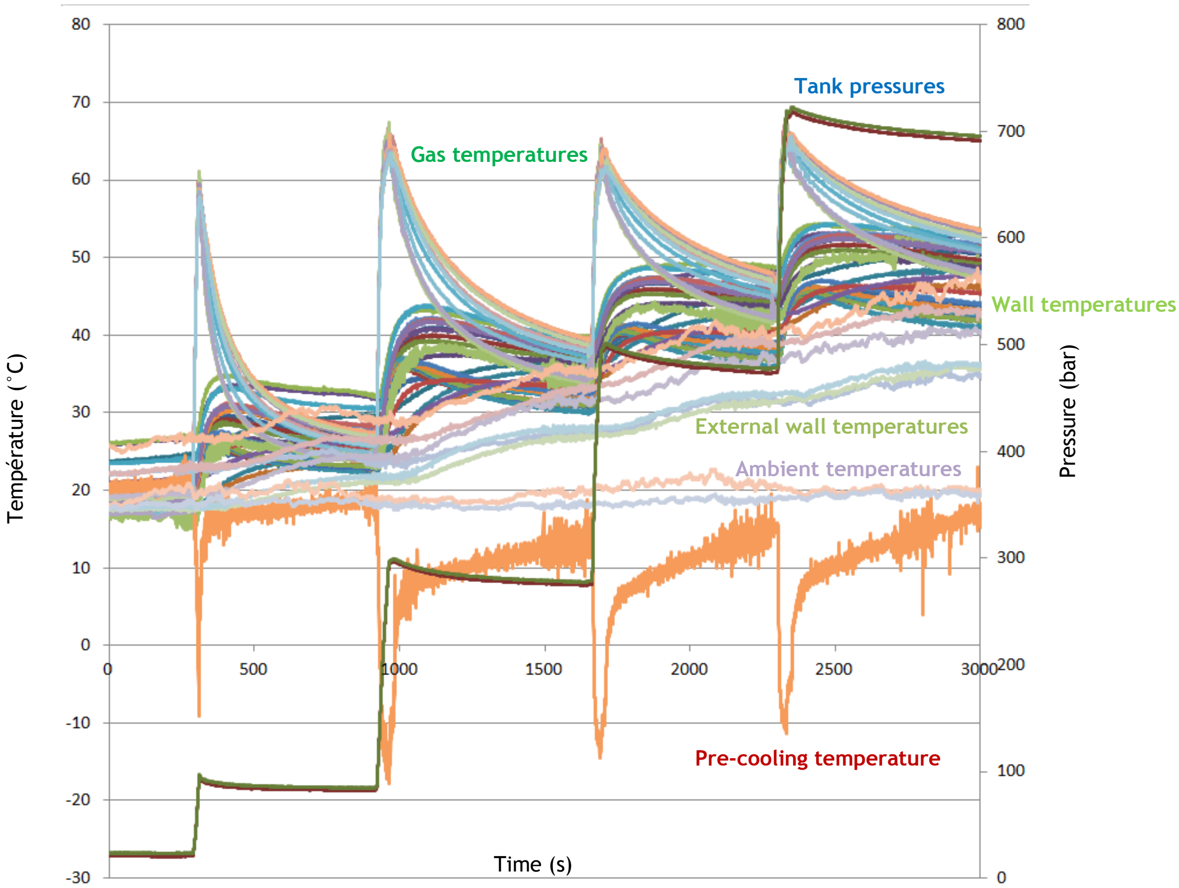


Figure 75: Fill SMV n°8 – pressure profile

Comments: this is a test with a pressure profile, with stops within the fuelling. The fuelling ramp rate was around 4,4 bar/s and the fuelling was stopped at 4 different pressure targets. The pre-cooling hardly reaches -20°C during the fuelling phases. We can see for each step the temperature increase followed by a stabilisation. We observe the short transition period of the gas temperature elevation.

Table 50: Defuelling n°4 details

Date	25th June
Afternoon – Defuelling n°4	13:20 – 14:20
Weather	North wind / ~26°C ambient
Stabilization duration	3 h 10 min recorded + night

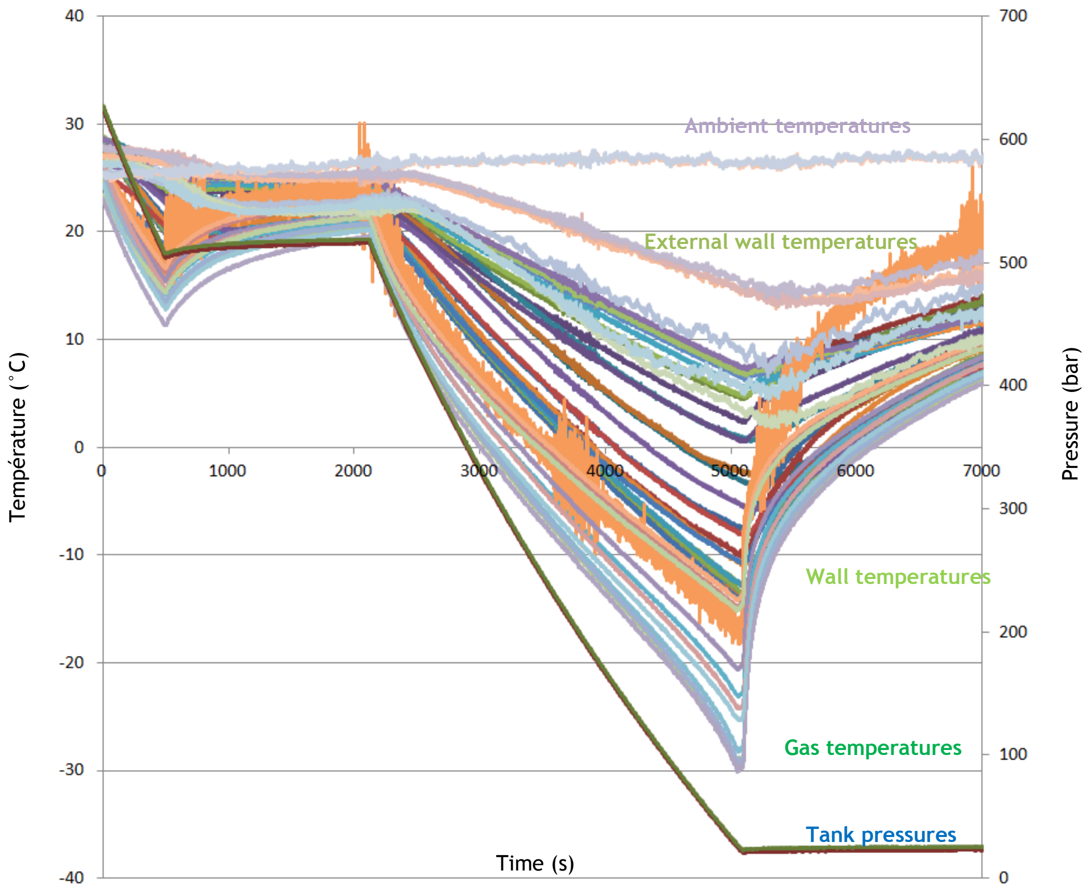


Figure 76: Defuelling n°4 – lower initial SOC

Comments: this test focuses on a lower initial state of charge, around 520 bar and 20°C initial conditions. The tank was first partially defuelled and left 25 min stabilizing. The defuelling started with an ambient / gas average temperature difference of ~ 5°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. The temperature behaviour is similar to the previous defuellings at the reference flowrate.

5.3.4.7 Fill SMV n°3+ Defuelling n°2 bis

Table 51: Fill SMV n°3 details

Date	26th June
Morning – Fill SMV n°3	08:20 – 08:25
Weather	No wind / ~18°C ambient
Stabilization duration	3 h 35 min

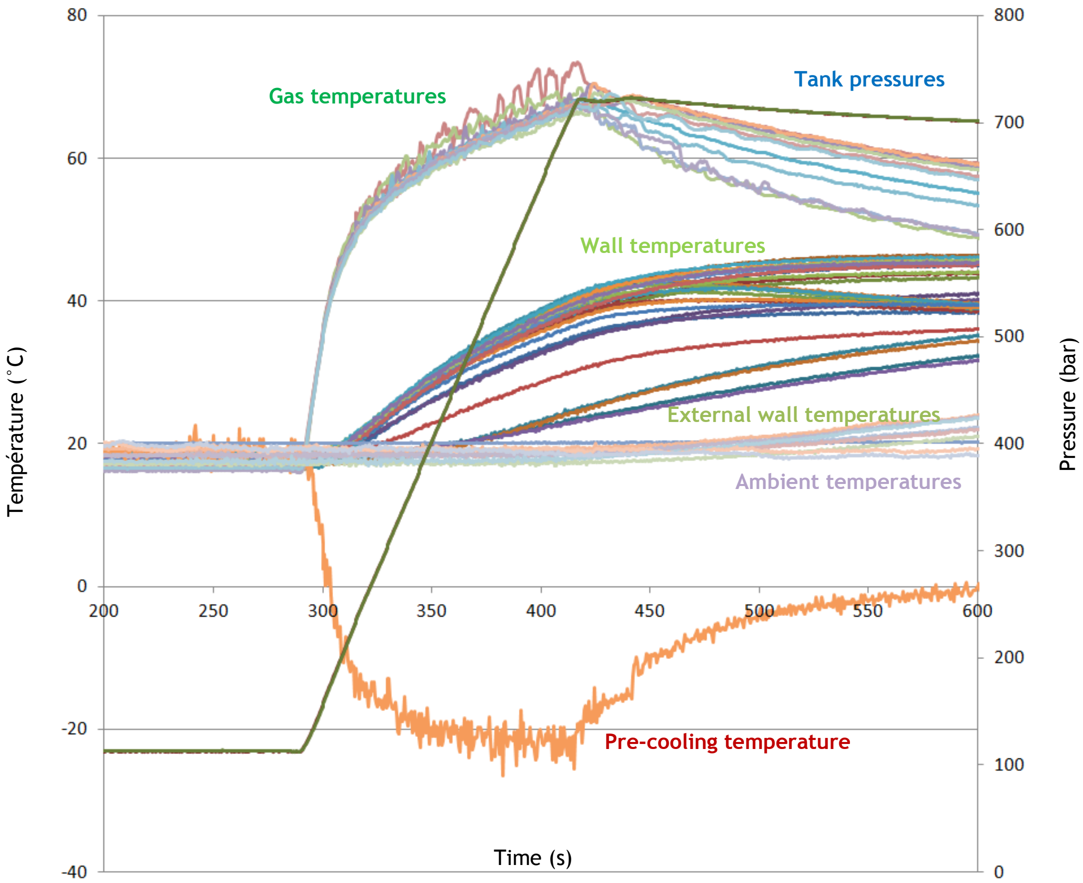


Figure 77: Fill SMV n°3 – higher initial pressure

Comments: a protection shield was placed around the tank to prevent sun radiation directly on the tank. This is a test with a higher initial pressure. The fuelling ramp rate was around 4,4 bar/s and it stopped on a pressure condition. The pre-cooling reaches -20°C. We don't see any stratification and we can on a first observation confirms that a higher initial pressure reduces the maximum final temperatures.

Table 52: Defuelling n°2 bis details

Date	26th June
Afternoon – Defuelling n°2 bis	12:00 – 12:55
Weather	No wind / ~23°C ambient
Stabilization duration	3 h 20 min recorded + night

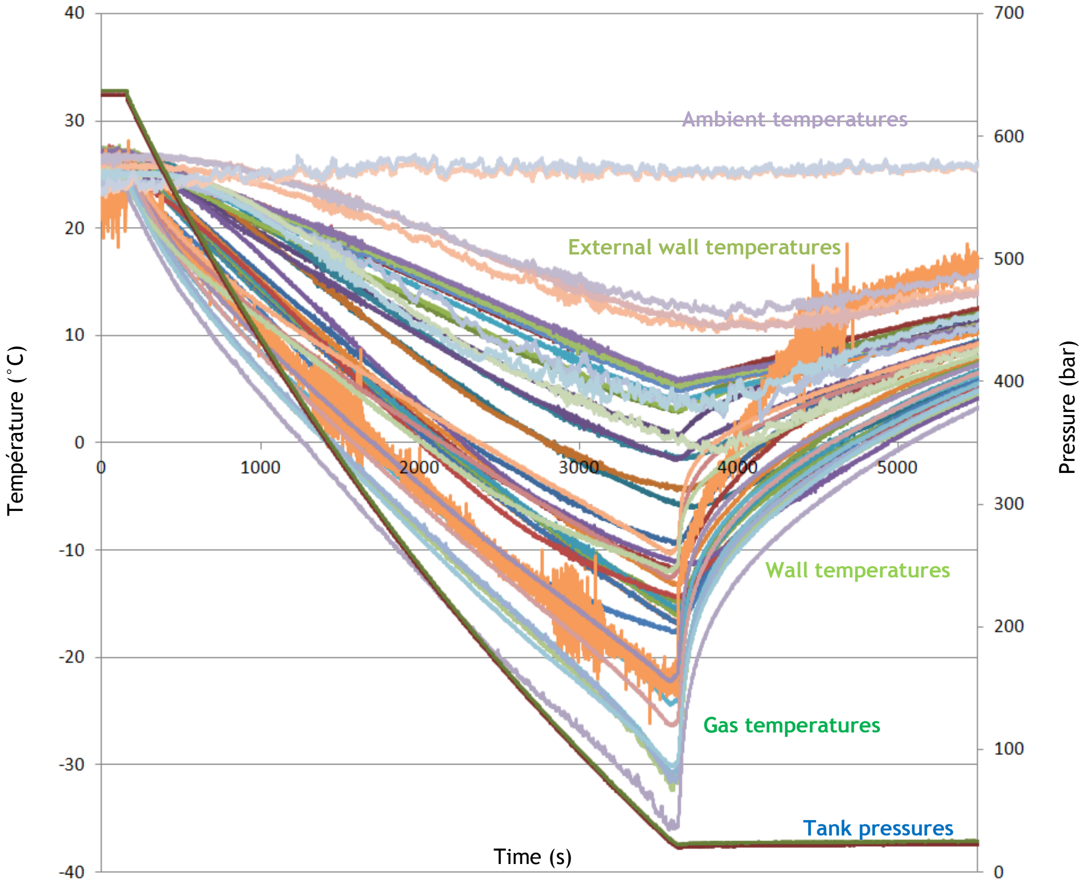


Figure 78: Defuelling n°2 bis – repeatability

Comments: there is no test specified for this defuelling, we thus reproduce the repeatability case. The defuelling started with an ambient / gas average temperature difference of ~ 2°C. The recording was stopped when this difference was less than 2°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. There is a good reproducibility.

5.3.4.8 Fill SMV n°4 + Defuelling n°3

Table 53: Fill SMV n°4 details

Date	29th June
Morning – Fill SMV n°4	09:10 – 09:15
Weather	No wind / ~19°C ambient
Stabilization duration	3 h 30 min

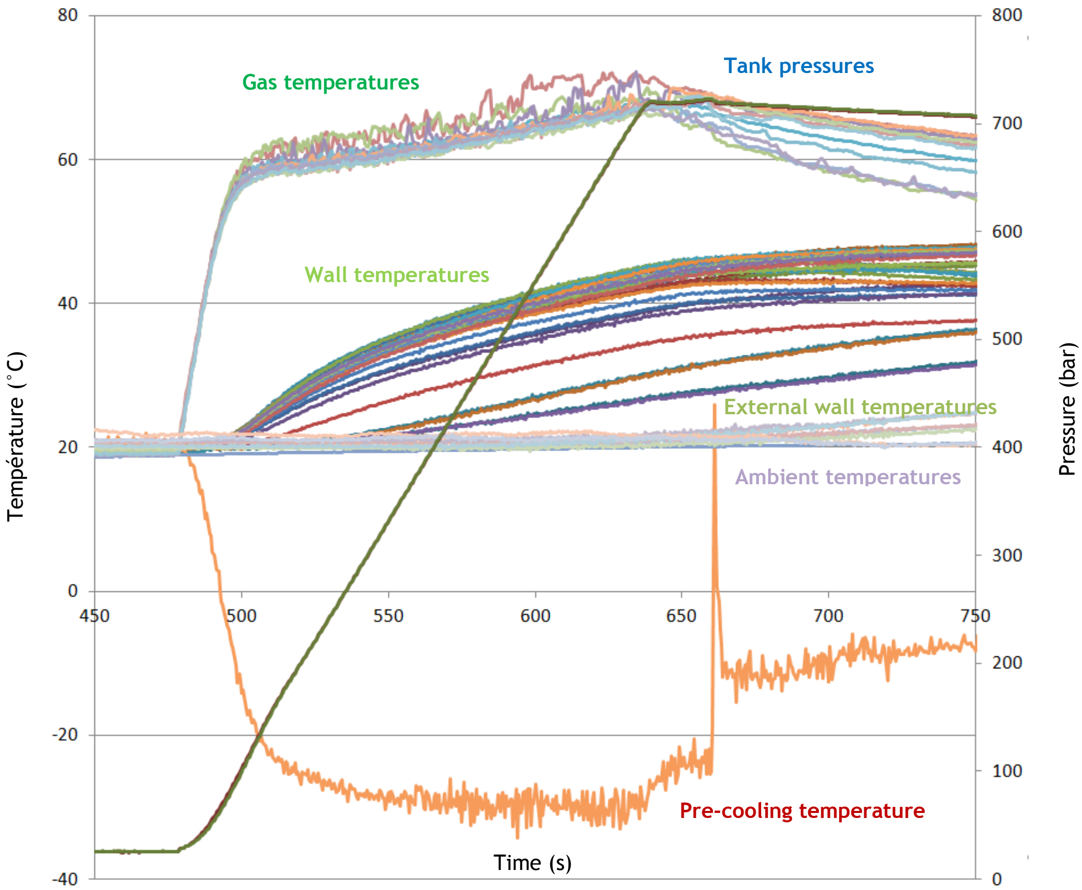


Figure 79: Fill SMV n°4 – colder pre-cooling

Comments: this is a test with lower pre-cooling, to evaluate the impact of an increased pre-cooling. The fuelling ramp rate was around 4,4 bar/s and it stopped on a pressure condition. The pre-cooling is reaches -30°C. We don't see any stratification and a first observation shows that the final temperatures are lower with more pre-cooling. The range of the decrease is proportional to the pre-cooling decrease.

Table 54: Defuelling n°3 details

Date	29th June
Afternoon – Defuelling n°3	12:40 – 13:55
Weather	Allmost no wind / ~27°C ambient
Stabilization duration	4 h 10 min recorded + night

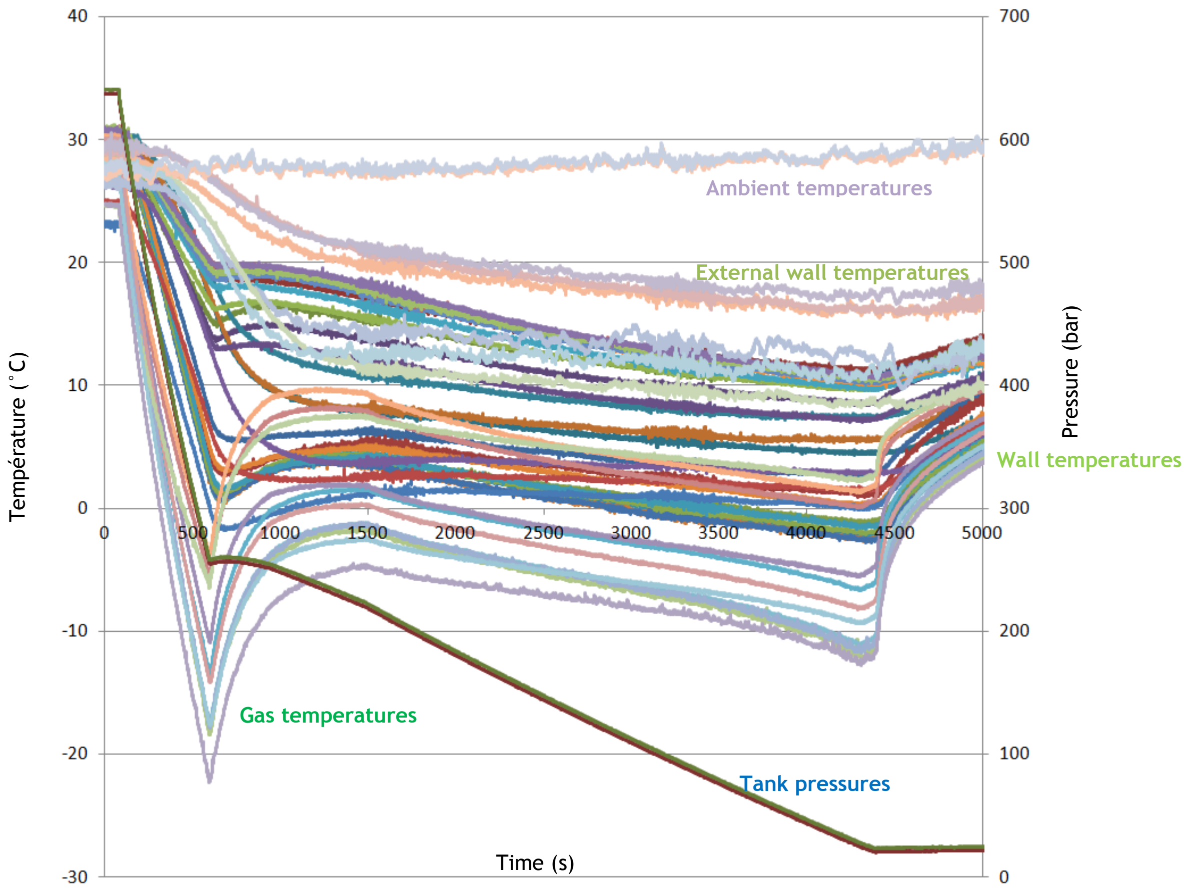


Figure 80: Defuelling n°3 – flowrate variation

Comments: this test is performed at the higher flowrate of 1,5 g/s at the beginning followed by a lower flowrate at 0,2 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 1°C. The recording was stopped when this difference was less than 1°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. The strategy defined here allows reducing quickly the pressure, while limiting the temperature decrease in the gas.

5.3.4.9 Fill SMV n°6+ Defuelling n°7

Table 55: Fill SMV n°6 details

Date	01st July
Morning – Fill SMV n°6	08:21 – 08:40
Weather	No wind / ~23°C ambient
Stabilization duration	4 h 00 min

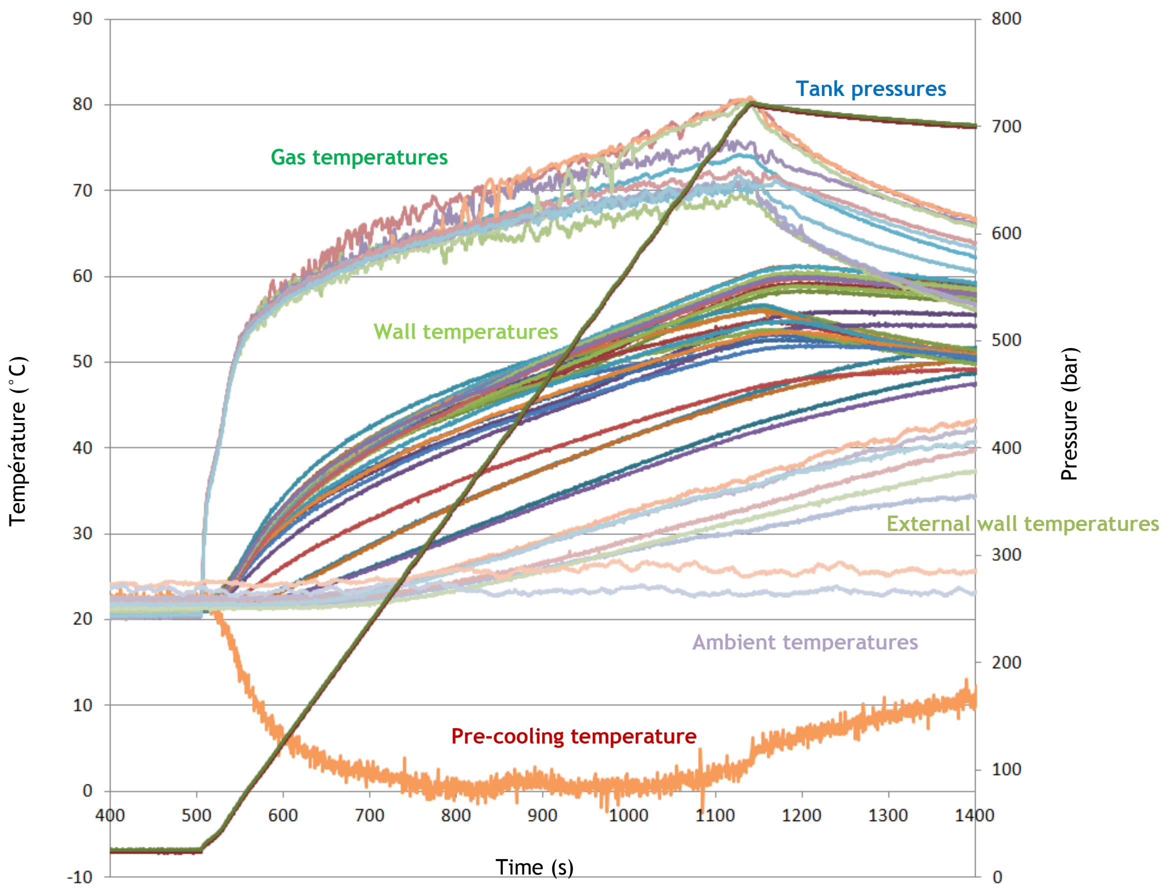


Figure 81: Fill SMV n°6 – no pre-cooling

Comments: this is a test without pre-cooling, to evaluate the impact of a reduce pre-cooling. The flowrate is also reduced to avoid overtemperatures. The fuelling ramp rate was around 1,1 bar/s and it stopped on a pressure condition. The pre-cooling is set at 0°C and considered as no pre-cooling. Stratification appears again and a first observation does not allow to clearly differentiate the impact of pre-cooling vs lower flow rate, except a temperature shift towards warmer temperatures.

Table 56: Defuelling n°7 details

Date	1st July
Afternoon – Defuelling n°7	12:45 – 16:20
Weather	North wind / ~30°C ambient
Stabilization duration	3 h 20 min recorded

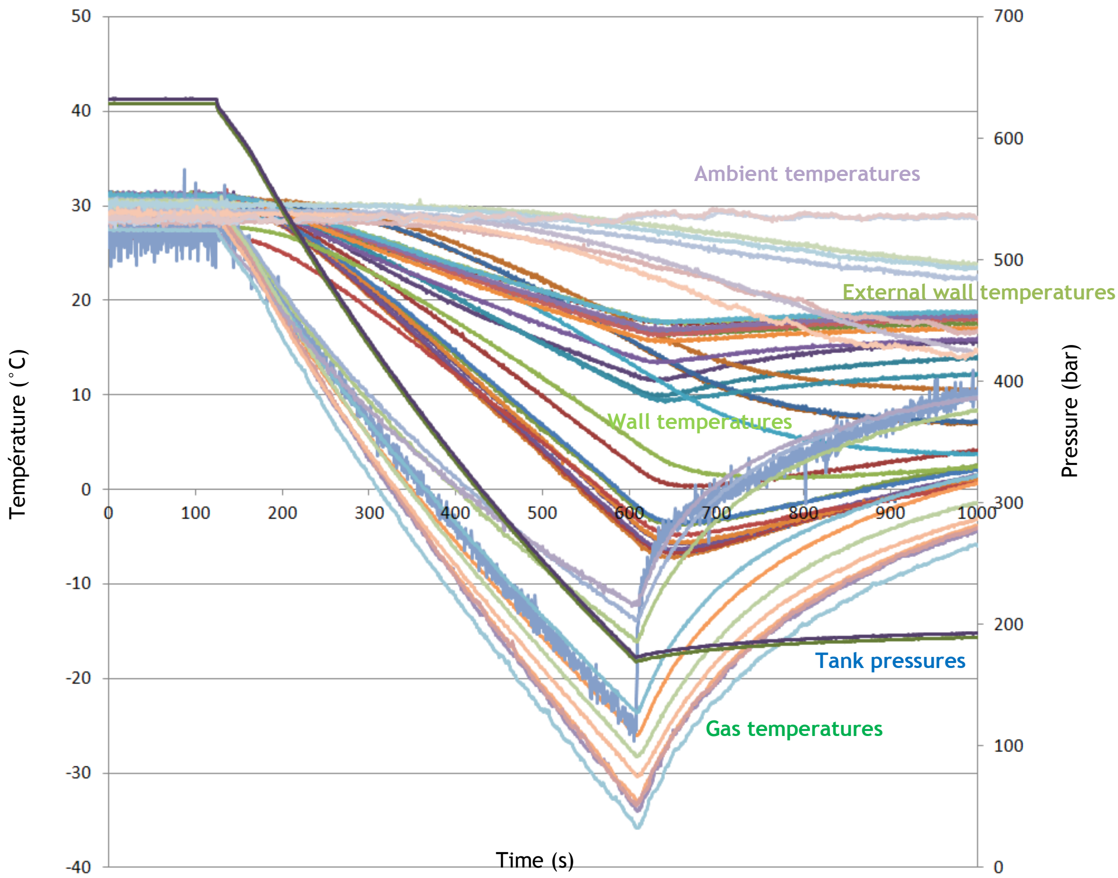


Figure 82: Defuelling n°7 – higher flowrate

Comments: this test is performed at the higher flowrate of 2g/s, with a stop on pressure at 200 bar to prevent any damage on the tank. The defuelling started with an ambient / gas average temperature difference of ~ 1°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. Similarly to a fast fuelling, the temperature difference, between the gas, the liner/composite wall and external wall are clearly differentiated.

Following this test, the tank was completely defuelled, purged with nitrogen. After that the 6mm injector replaced the 3mm injector and the tank was prepared at 20 bar for the next day.

5.3.4.10 Fill FTD n°3+ Defuelling n°6 bis

Table 57: Fill FTD n°3 details

Date	02nd July
Morning – Fill FTD n°3	08:55 – 09:05
Weather	North wind / ~22°C ambient
Stabilization duration	4 h 20 min

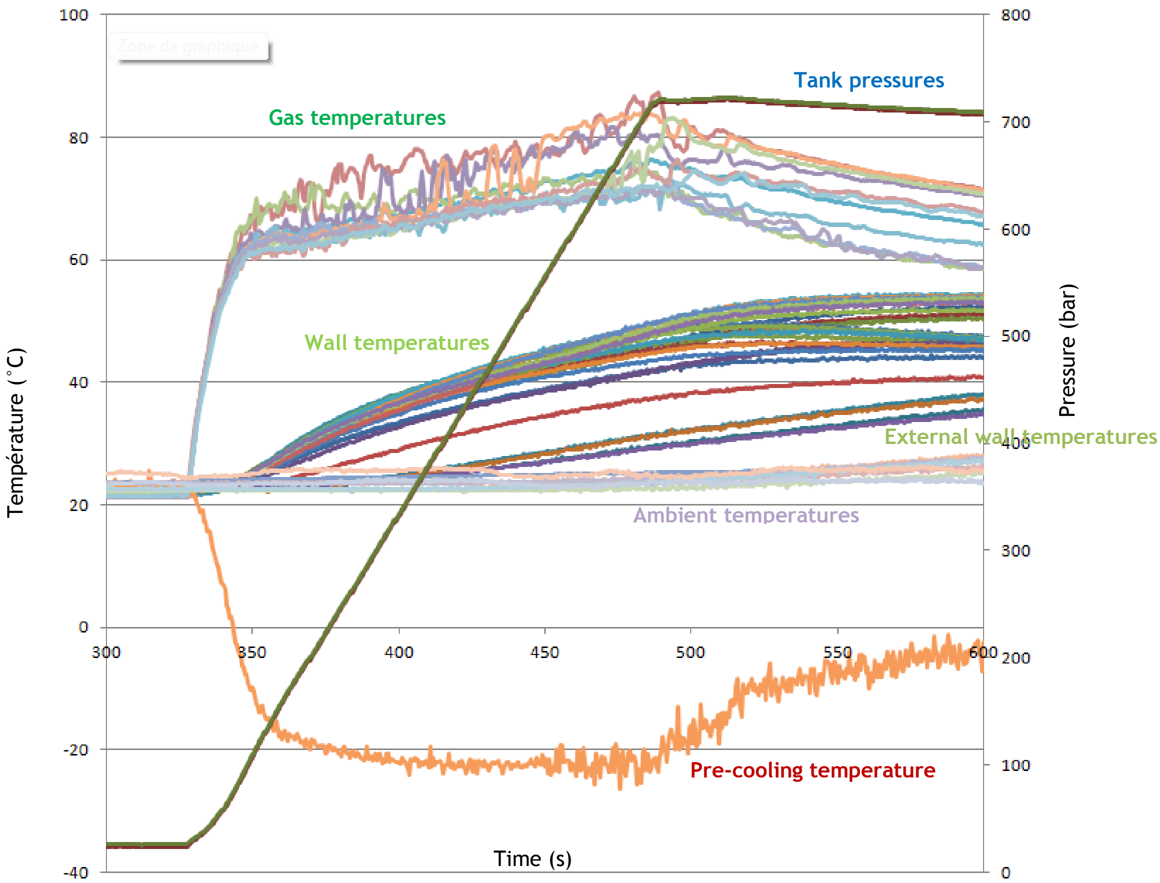


Figure 83: Fill FTD n°3 – 6mm injection diameter

Comments: this test is the reference case with a 6mm injection diameter, performed to evaluate the impact of the injection diameter. The fuelling ramp rate was around 4,4 bar/s and it stopped on a pressure condition. The pre-cooling reaches -21°C. Stratification appears after a certain fuelling time, showing the impact of injection diameter.

Table 58: Defuelling n°6 bis details

Date	2nd July
Afternoon – Defuelling n°6 bis	12:45 – 16:20
Weather	Strong north wind / ~31°C ambient
Stabilization duration	1 h 20 min recorded + night

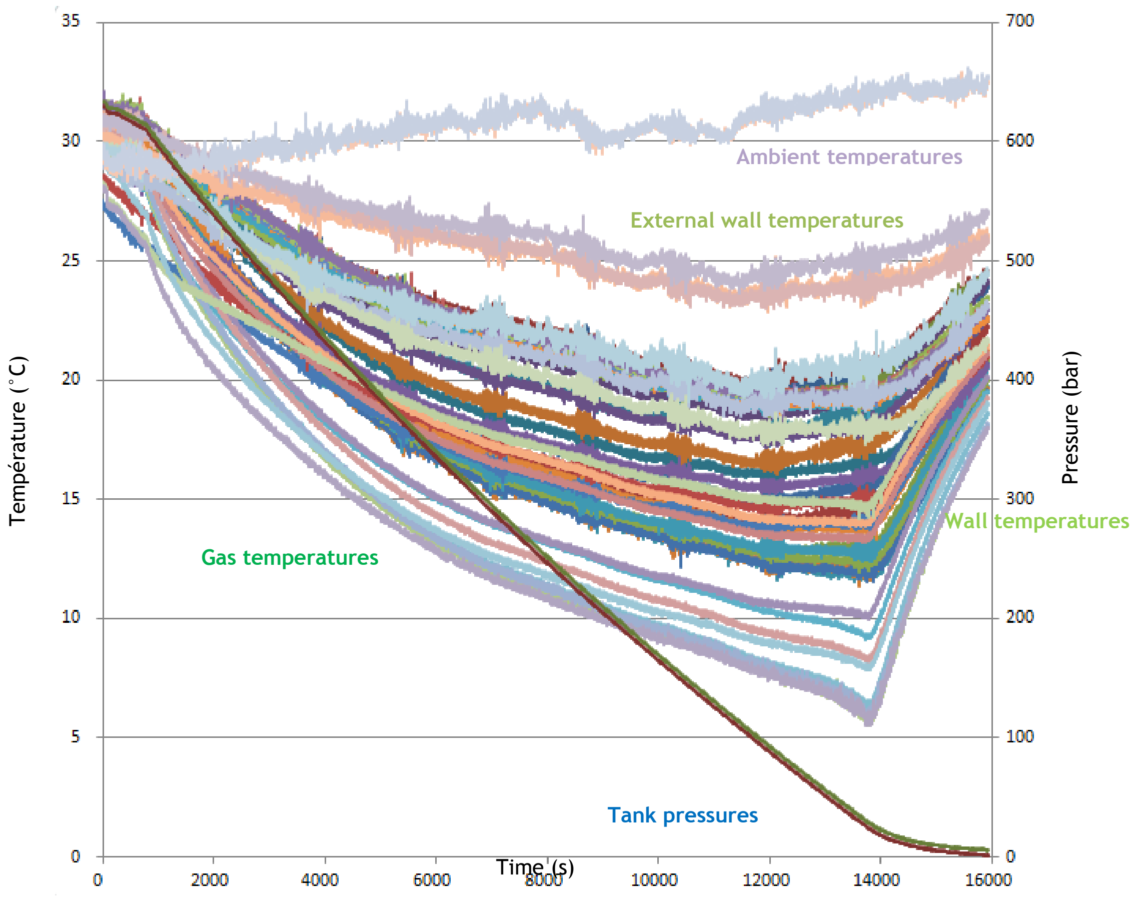


Figure 84: Defuelling n°6 bis – 6mm injector slow defuelling

Comments: this test is performed at the slower flowrate of 0,125g/s. This test was not specified in test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 2°C. A failure in the ramp control led to a defuelling down to 0 bar. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed. As the ambient temperature was high and the defuelling rate slow the temperatures reached are staying over 0°C.

5.3.4.11 Fill FTD n°4+ Defuelling n°1 bis

Table 59: Fill FTD n°4 details

Date	03rd July
Morning – Fill FTD n°4	08:45 – 09:00
Weather	Slight north wind / ~25°C ambient
Stabilization duration	3 h 20 min

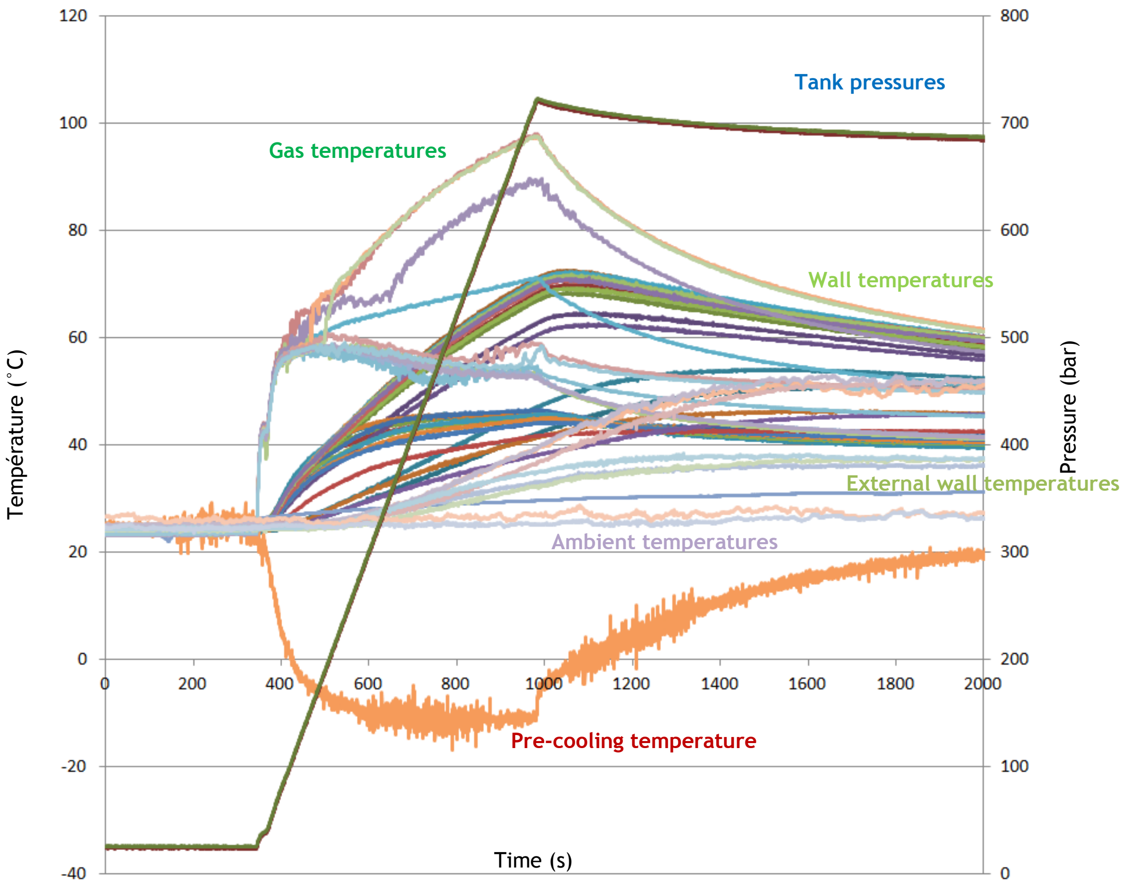


Figure 85: Fill FTD n°4 – 6mm injector slower flowrate

Comments: **t**his test is performed at the low flowrate with a 6mm diameter injector, to compare it with the case with the 3mm diameter injector. The fuelling ramp rate was around 1,1 bar/s and it stopped on a pressure condition. The pre-cooling reaches -10°C, which was not as cold as specified. Stratification appears clearly, showing that the lower flowrate increases the stratification effect.

Table 60: Defuelling n°1 bis details

Date	3rd July
Afternoon – Defuelling n°1 bis	12:20 – 13:10
Weather	North wind / ~30°C ambient
Stabilization duration	4 h 00 min recorded

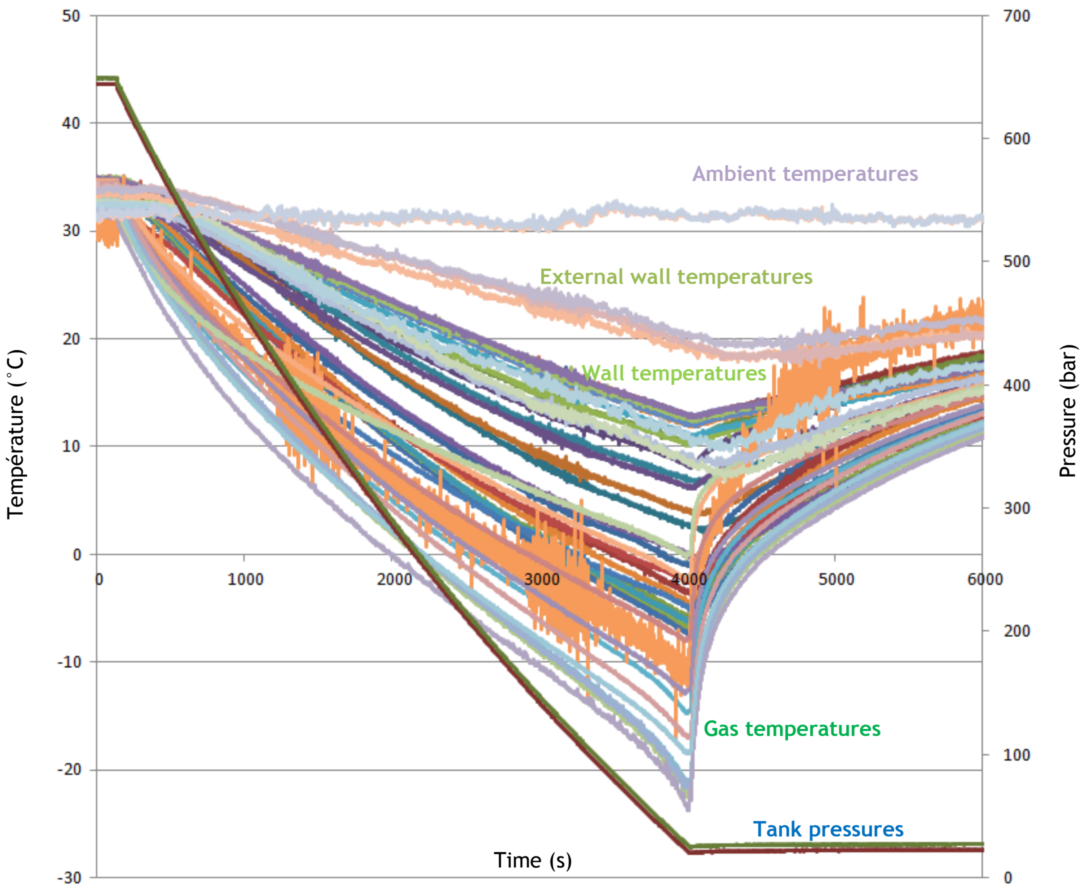


Figure 86: Defuelling n°1 bis – reference case with 6mm injection

Comments: this test is performed at the reference flowrate of 0,375g/s. This test was not specified in the test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 2°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

Following this test, the tank was completely defuelled, purged with nitrogen. After that the 4 times 3mm radial injector replaced the 6mm injector and the tank was prepared at 20 bar for the next day.

5.3.4.12 Fill FTD n°7+ Defuelling n°6 bis

Table 61: Fill FTD n°7 details

Date	6th July
Morning – Fill FTD n°7	08:55 – 09:15
Weather	Slight north wind / ~24°C ambient
Stabilization duration	4 h 10 min

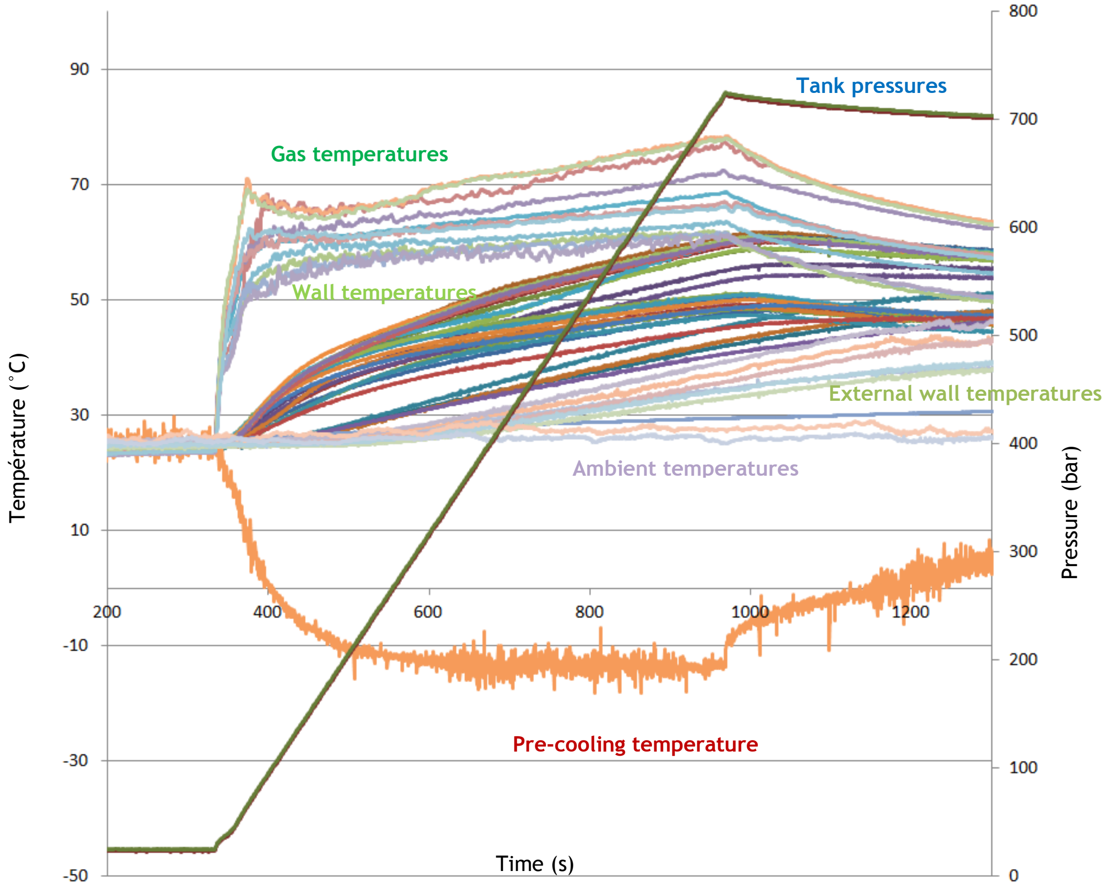


Figure 87: Fill FTD n°7 – radial injector slower flowrate

Comments: this test is performed at the low flowrate with a radial injector (4x3mm) injector, to compare it with the cases with the 3mm and the 6mm diameter injector. The fuelling ramp rate was around 1,1 bar/s and it stopped on a pressure condition. The pre-cooling reaches -12°C, which was not as cold as specified. Stratification appears also in this case, showing that the lower flowrate increases the stratification effect. The clear impact of the radial injection is difficult to identify at a first look.

Table 62: Defuelling n°6 bis details

Date	6th July
Afternoon – Defuelling n°6 bis	12:25 – 13:15
Weather	Sligth north wind / ~31°C ambient
Stabilization duration	4 h 45 min recorded + night

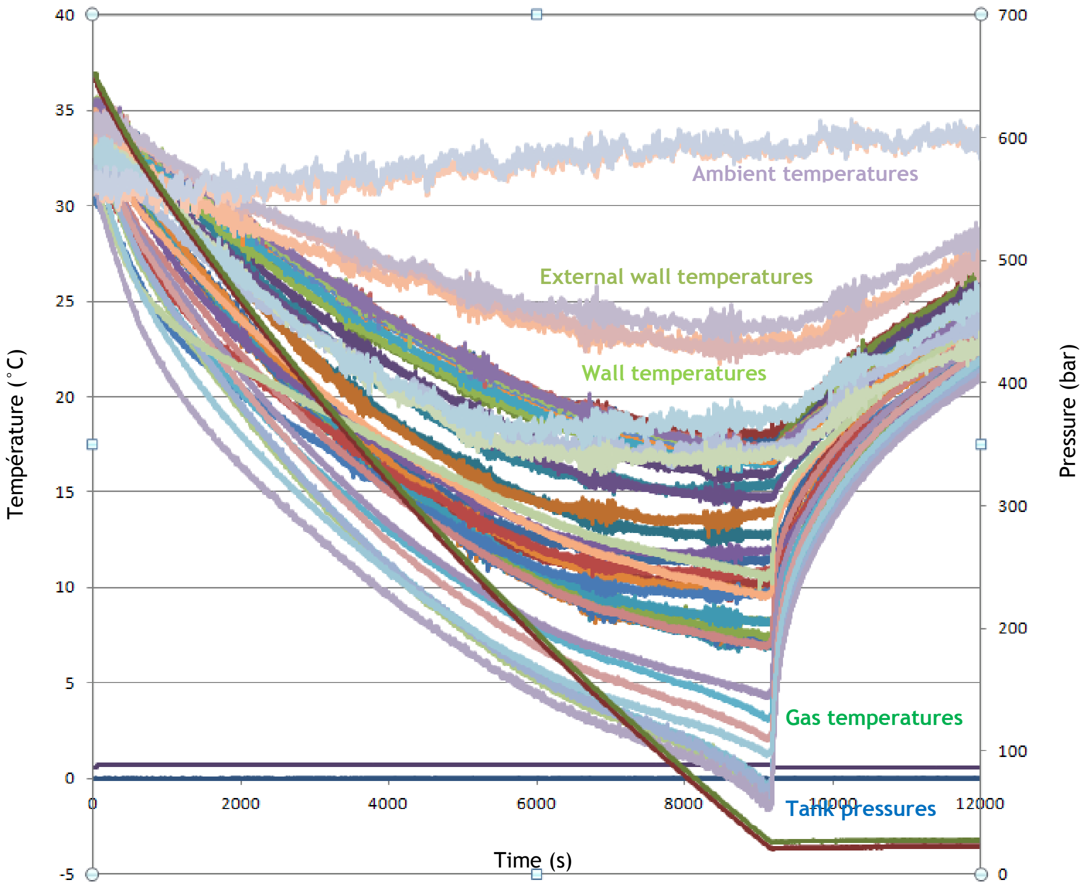


Figure 88: Defuelling n°6 bis – slow flow rate with radial injection

Comments: this test is performed at the slower flowrate of 0,125g/s. This test was not specified in the test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 3°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter color). On some of the sensors some noise could be observed.

5.3.4.13 Fill High Flow n°1+ Defuelling n°1 bis

Table 63: Fill HF n°1 details

Date	7th July
Morning - Fill HF n°1	08:55 - 09:00
Weather	Slight south wind / ~26°C ambient
Stabilization duration	4 h 00 min

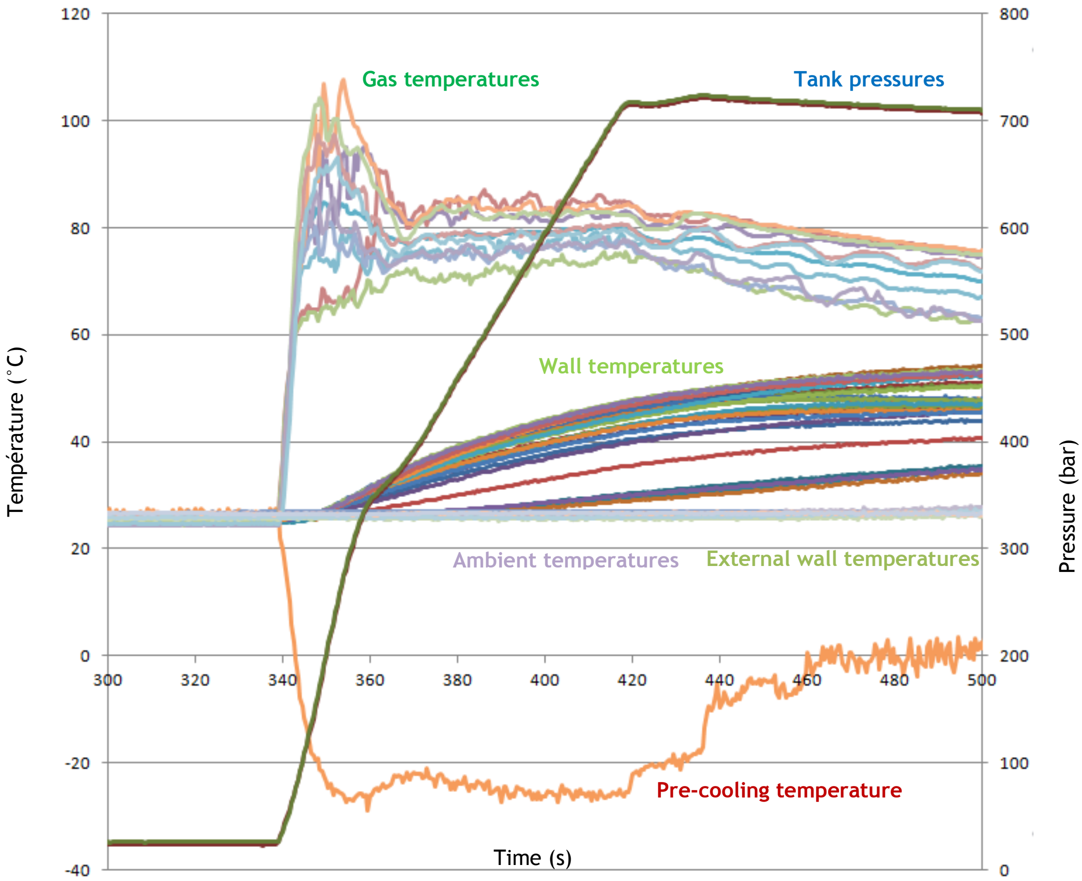


Figure 89: Fill HF n°1 – high flowrate 1

Comments: this test is performed at an average flowrate of 10g/s, to evaluate the impact of extreme flowrate (to be multiplied by the number of tanks in a vehicle). The fuelling ramp rate was around 6,8 bar/s and it stopped on a pressure condition. There is a ramp correction after the beginning to stick to the specification. The pre-cooling reaches -26°C. Some stratification appears also in this case, this might be caused by the radial injector, mixing flows in a specific way. We can also observe the delay of temperature convection through the wall, due to the fast flow.

Table 64: Defuelling n°1 bis details

Date	7th July
Afternoon – Defuelling n°1 bis	12:00 – 12:50
Weather	North wind / ~32°C ambient
Stabilization duration	5 h 40 min recorded + night

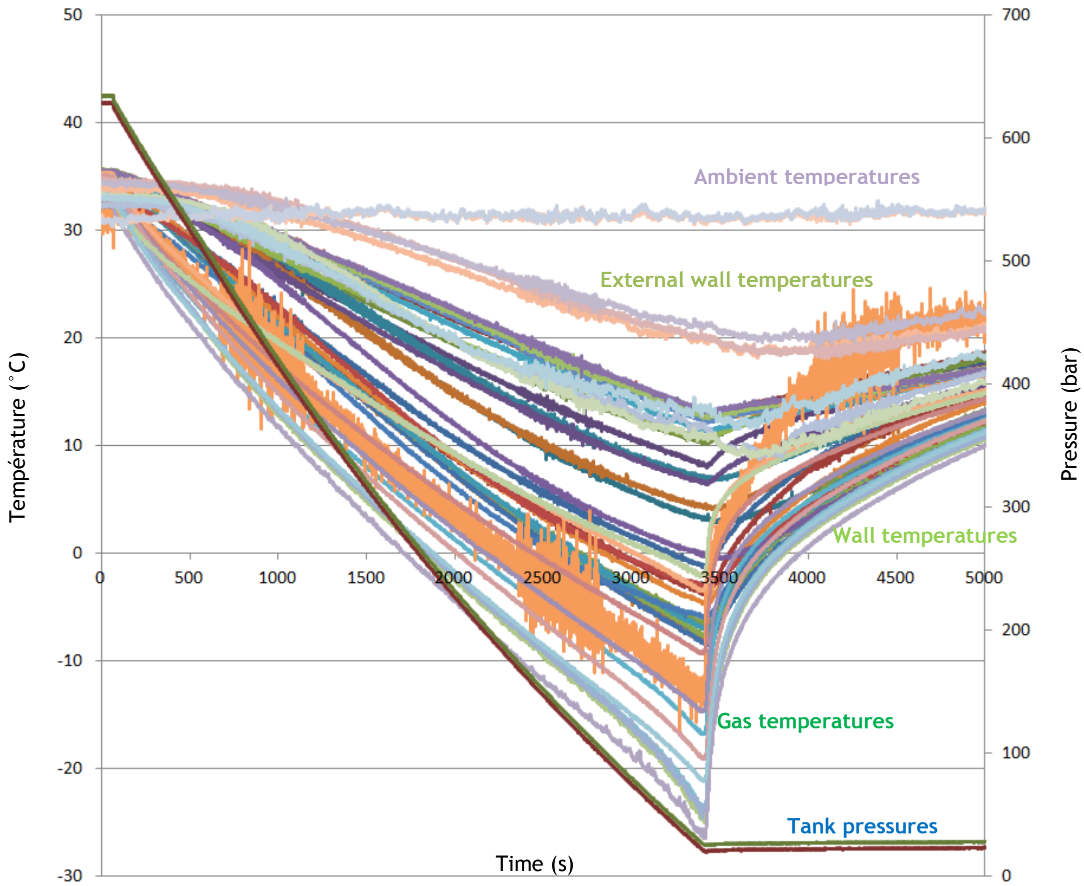


Figure 90: Defuelling n°1 bis – reference case with radial injection

Comments: this test is performed at the reference flowrate of 0,375g/s. This test was not specified in the test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 3°C. The recording was stopped when this difference was less than 2°C. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

5.3.4.14 Fill High Flow n°2+ Defuelling

Table 65: Fill HF n°2 details

Date	8^{th} July
Morning – Fill HF n°2	11:59 – 12:05
Weather	Strong north wind / ~23°C ambient
Stabilization duration	1 h 30 min

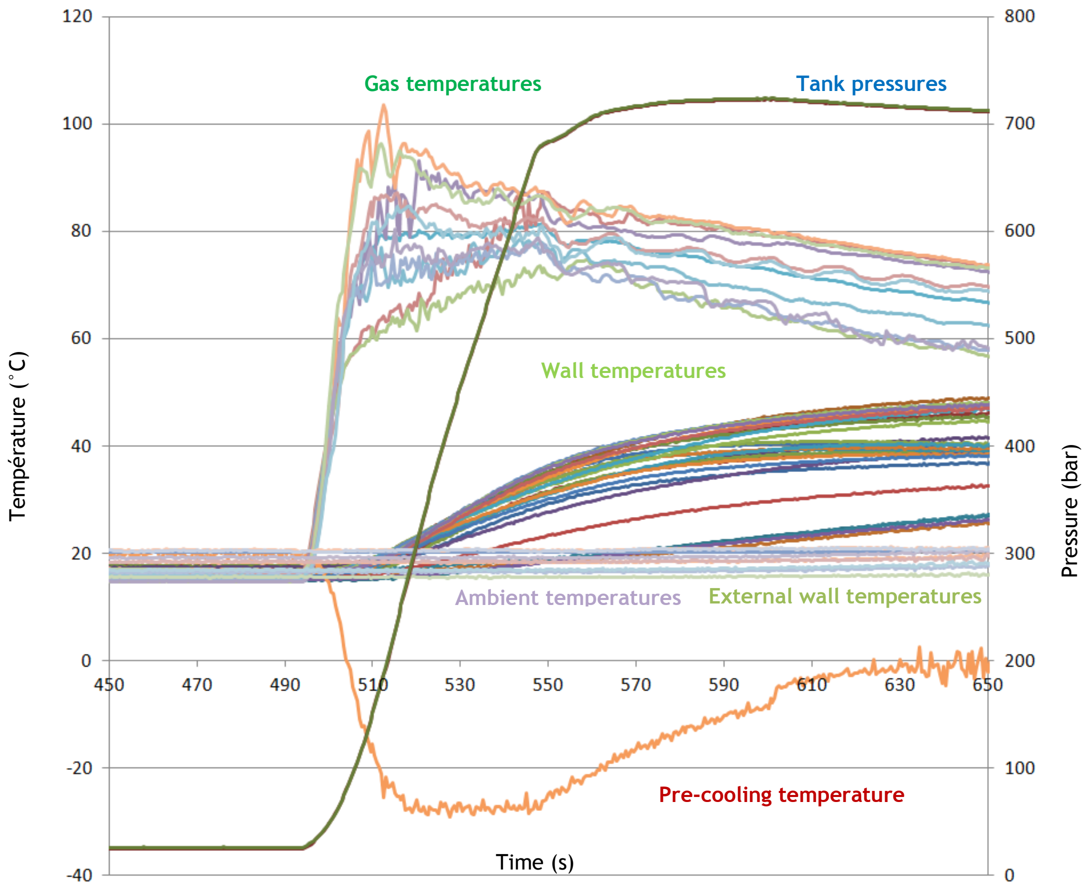


Figure 91: Fill HF n°2 – high flowrate

Comments: this test is performed at an average flowrate of 20g/s, to evaluate the impact of extreme flowrate (to be multiplied by the number of tanks in a vehicle). The fuelling ramp rate was around 13,4 bar/s and it stopped on a pressure condition. The pre-cooling reaches -27°C. Some stratification appears also in this case, this might be caused by the radial injector, mixing flows in a specific way. We can also observe the delay of temperature convection through the wall, due to the fast flow. Similar behaviour as previous test

Table 66: Defuelling details

Date	8th July
Afternoon – Defuelling	13:50 – 14:15
Weather	Strong north wind / ~20°C ambient
Stabilization duration	2 h 45 min recorded + night

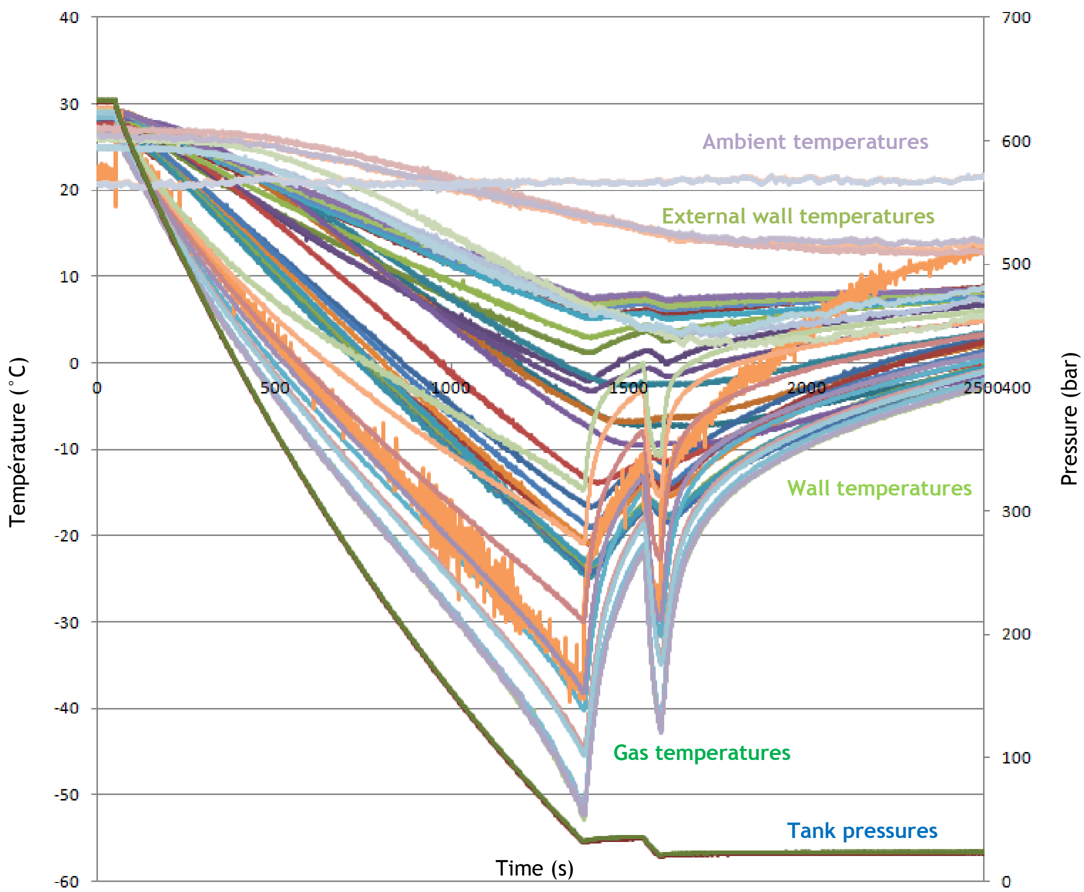


Figure 92: Defuelling – 1,5 g/s defuelling

Comments: this test is performed at a flowrate of 1,5g/s. This test was not specified in the test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 10°C. The recording was stopped when this difference was less than 3°C. There is a stop at -40°C average in the tank and then a restart. We see the temperature gradient between the gas and wall temperatures. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

5.3.4.1 Fill High Flow n°3+ Defuelling

Table 67: Fill HF n°3 details

Date	9th July
Morning – Fill HF n°3	09:05 – 09:10
Weather	North wind / ~20°C ambient
Stabilization duration	4 h 05 min

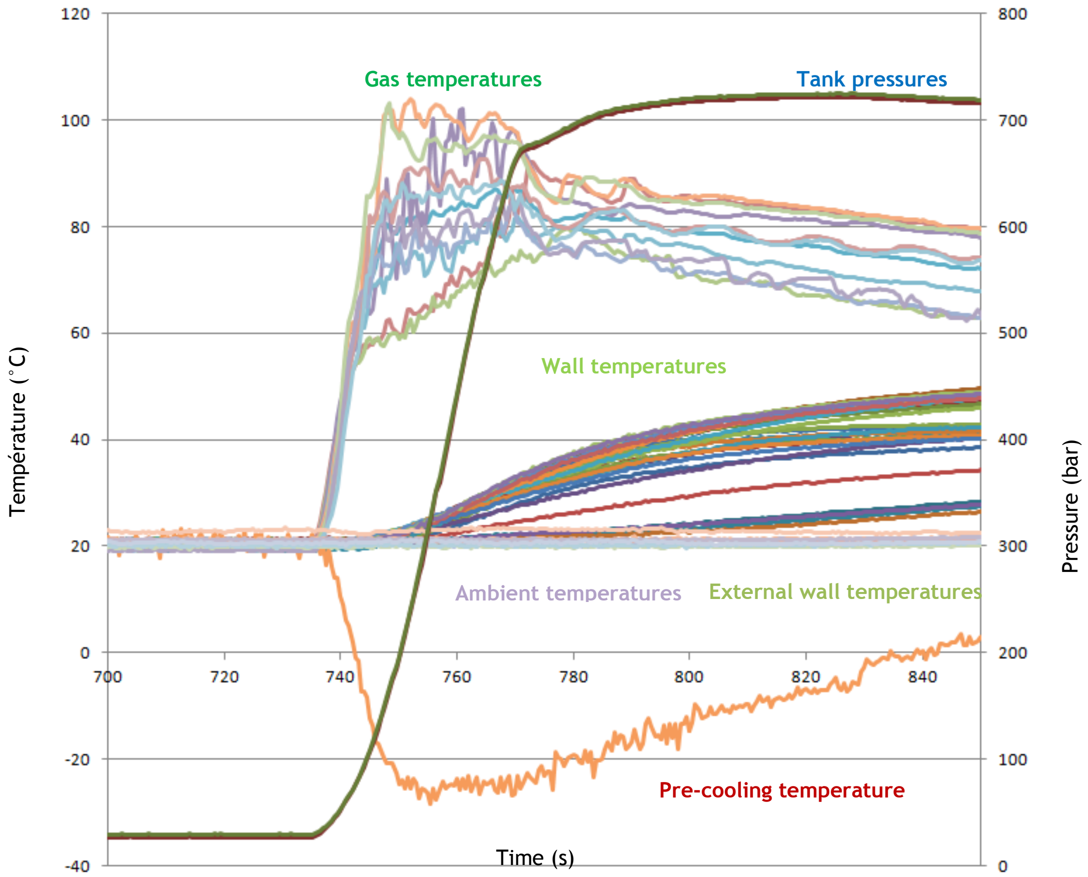


Figure 93:: Fill HF n°3 – high flowrate

Comments: this test is performed at an average flowrate of 30g/s, to evaluate the impact of extreme flowrate (to be multiplied by the number of tanks in a vehicle). This is the highest flow rate performed, fuelling in less than 1 min. The fuelling ramp rate was around 20,3 bar/s and it stopped on a pressure condition. The pre-cooling reaches -26°C. Some stratification appears also in this case, this might be caused by the radial injector, mixing flows in a specific way. We can also observe the delay of temperature convection through the wall, due to the fast flow. Similar behaviour as previous tests.

Table 68: Defuelling details

Date	9th July
Afternoon – Defuelling	13:20 – 13:40
Weather	Strong north wind / ~24°C ambient
Stabilization duration	No

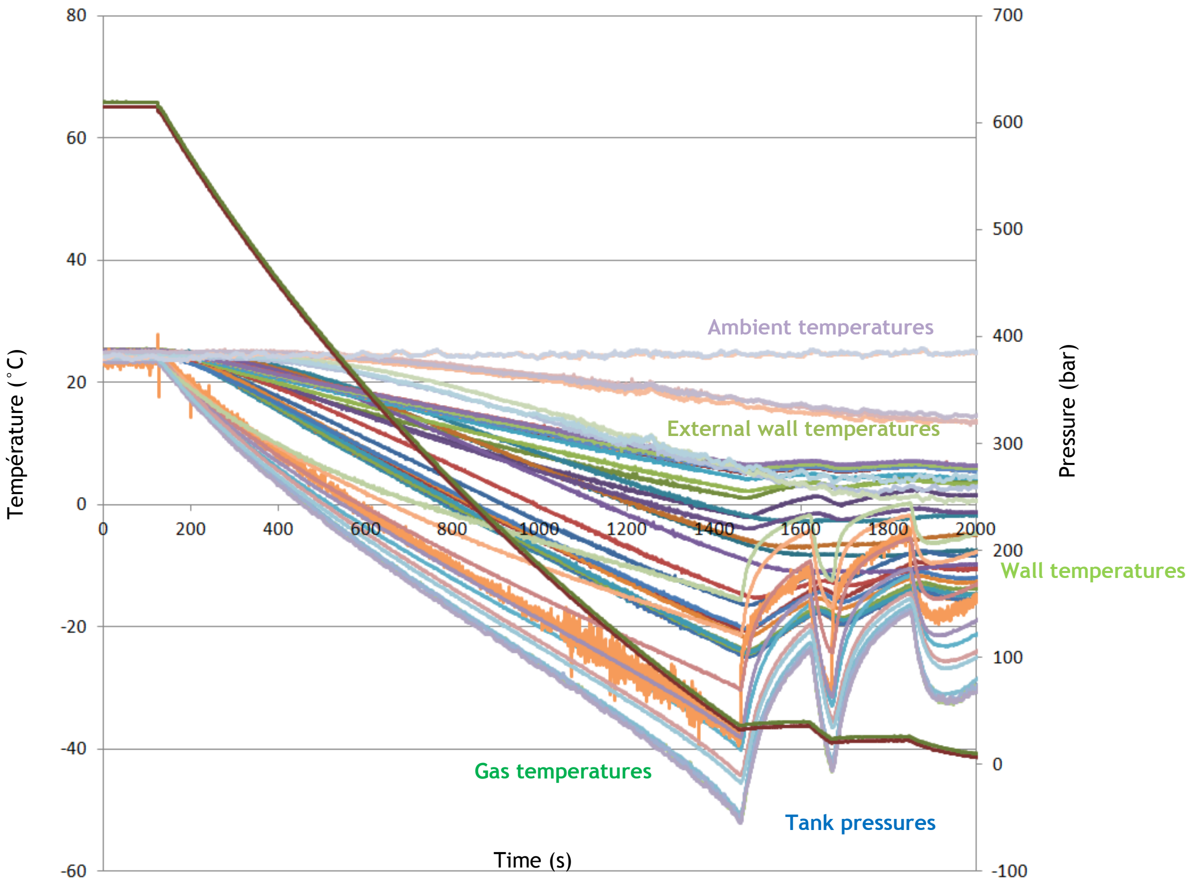


Figure 94: Defuelling – 1,5 g/s defuelling

Comments: this test is performed at a flowrate of 1,5g/s. This test was not specified in the test matrix. The defuelling started with an ambient / gas average temperature difference of ~ 1°C. There is a stop at -40°C average in the tank and then a restart, before the final defuelling. We see the temperature gradient between the gas and wall temperatures. We can also see here the temperature stratification with wall temperature being colder at the bottom of the tank than gas temperatures at the top of the tank. A similar effect can be noticed between liner/composite wall and external wall temperatures (lighter colors). On some of the sensors some noise could be observed.

Once the tests finished a complete defuelling was performed and the tank purged and packed once the instrumentation was removed. All the thermocouples except one of the external wall temperatures TT770 didn't move during the experiments. The tape of TT770 looked slightly loose.

5.4 Test campaign on Type IV large tank at AL-aT

5.4.1 Introduction

In the following section we present the tests performed with the Hexagon Lincoln 531L large cylinder. It began with the test bench installation and adjustment, following the short tank test and the sensor calibration check, followed by the specified testing. Finally the recorded results will be presented.

5.4.2 Test preparation

The fuelling installation was prepared and adapted to place the 531L tank instead of the 36L tank. Particularly the scale was removed. Another thermocouple tree adjusted to measure in the vertical plan was installed in the tank, as shown on Figure 95.

Figure 95: 531L tank installation

The thermocouple tree, as well as the inlet plug are mounted with metal to metal sealings. The pressure sensors are then installed on the inlet line and at the back of the tank. In addition 6 thermocouples are stick on the external wall with aluminium tape, 3 on the top (front dome, back dome and middle) and 3 at the bottom (front dome, back dome and middle). The external wall thermocouples are made of thin plate helping to have a good contact with the tank. The 2 thermocouples for ambient temperature measurement are already installed, one in the front area of the tank and another in the back area of the tank. Each thermocouple was then tested and connected. All thermocouples were working Figure 96 shows the finally installed tank and Figure 97 shows the Process and Instrument Diagram of the test bench.

Figure 96: Finalized installation

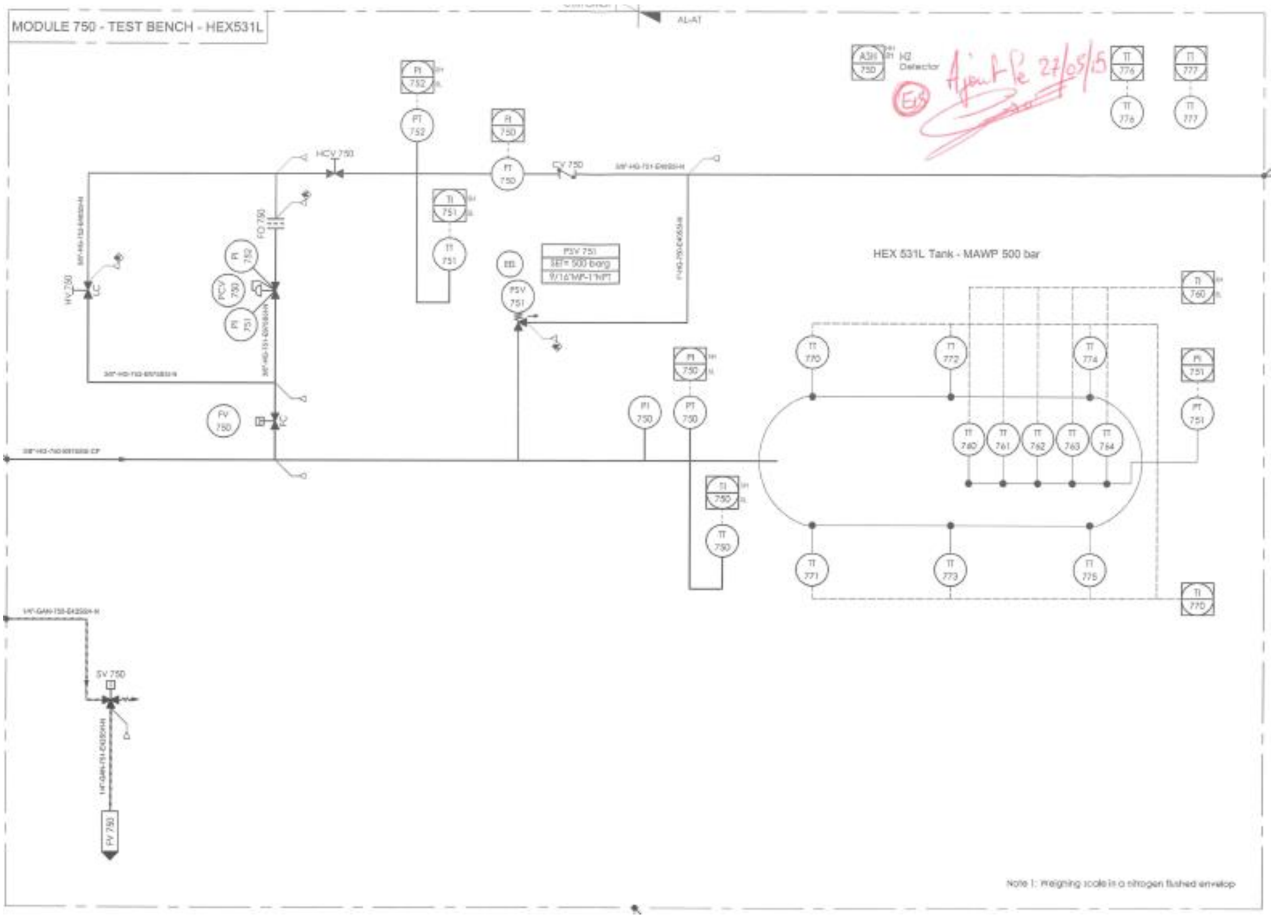


Figure 97: Installation P&ID

In Figure 98 and 99 associated with Table 69, give the detailed position of the thermocouple measurements of the tank.

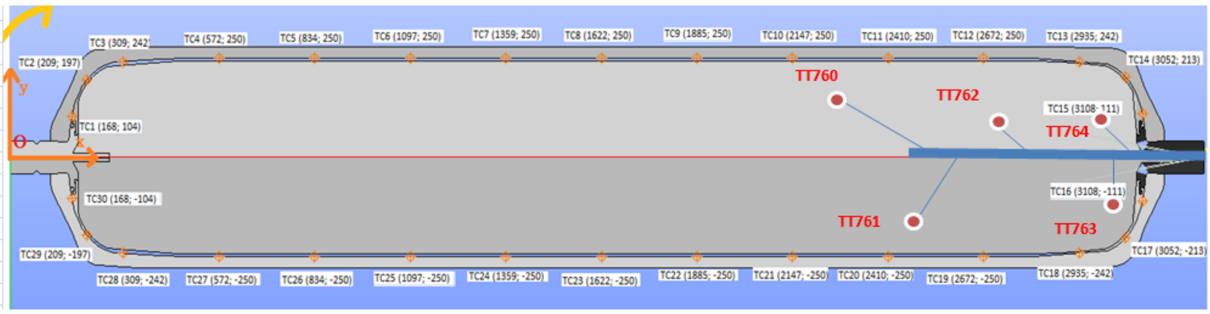


Figure 98: Position of Internal thermocouples (TT760 - TT765) and thermocouples placed between liner and wrapping (TC)

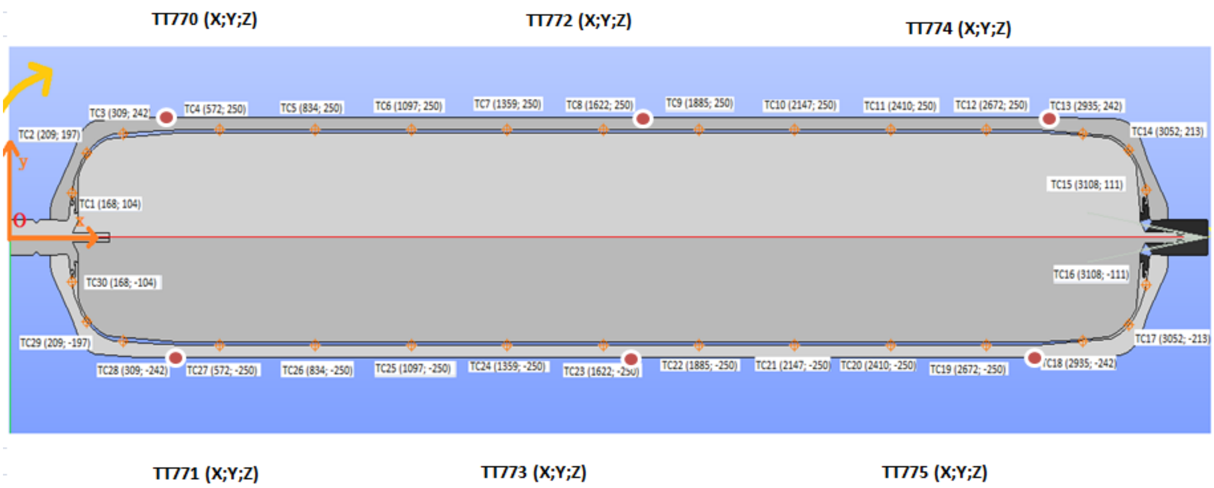


Figure 99: Position of External Thermocouples (TT770 - TT775) and thermocouples placed between liner and wrapping (TC)

Table 69: Position of the different tank thermocouples in (mm)

Thermocouple n°	x position	y position	z position
Gas temperature			
TT760	2592	0	-240
TT761	2742	-207	120
TT762	2877	0	-60
TT763	3042	-60	0
TT764	3007	0	-120
Ext wall temperature			
TT770	360	282,7	0
TT771	360	-282,7	0
TT772	1750	282,7	0
TT773	1650	-282,7	0
TT774	2890	282,7	0
TT775	2890	-282,7	0
Liner temperature			
TC1	168	104	0
TC2	209	197	0
TC3	309	242	0
TC4	572	250	0
TC5	834	250	0
TC6	1097	250	0
TC7	1359	250	0
TC8	1622	250	0
TC9	1885	250	0
TC10	2147	250	0
TC11	2410	250	0
TC12	2672	250	0
TC13	2935	242	0
TC14	3052	213	0

TC15	3108	111	0
TC16	3108	-111	0
TC17	3052	-213	0
TC18	2935	-242	0
TC19	2672	-250	0
TC20	2410	-250	0
TC21	2147	-250	0
TC22	1885	-250	0
TC23	1622	-250	0
TC24	1359	-250	0
TC25	1097	-250	0
TC26	834	-250	0
TC27	572	-250	0
TC28	309	-242	0
TC29	209	-197	0
TC30	73	-104	0

In addition to the thermocouples, all other elements position were identified, as shown in Figure 100, 101 and 102. Table 70 gives the position of the equipments on lines.

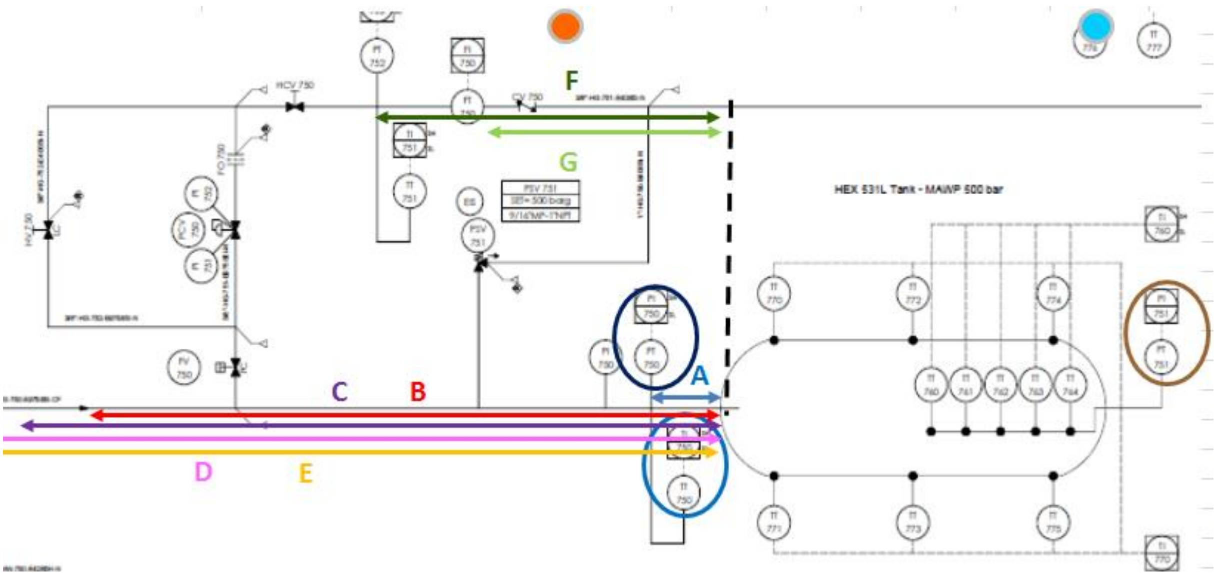


Figure 100: Position of the pressure, auxiliary temperature and mass flow meter measurement points

Figure 101: Picture of the equipment positions – Part 1

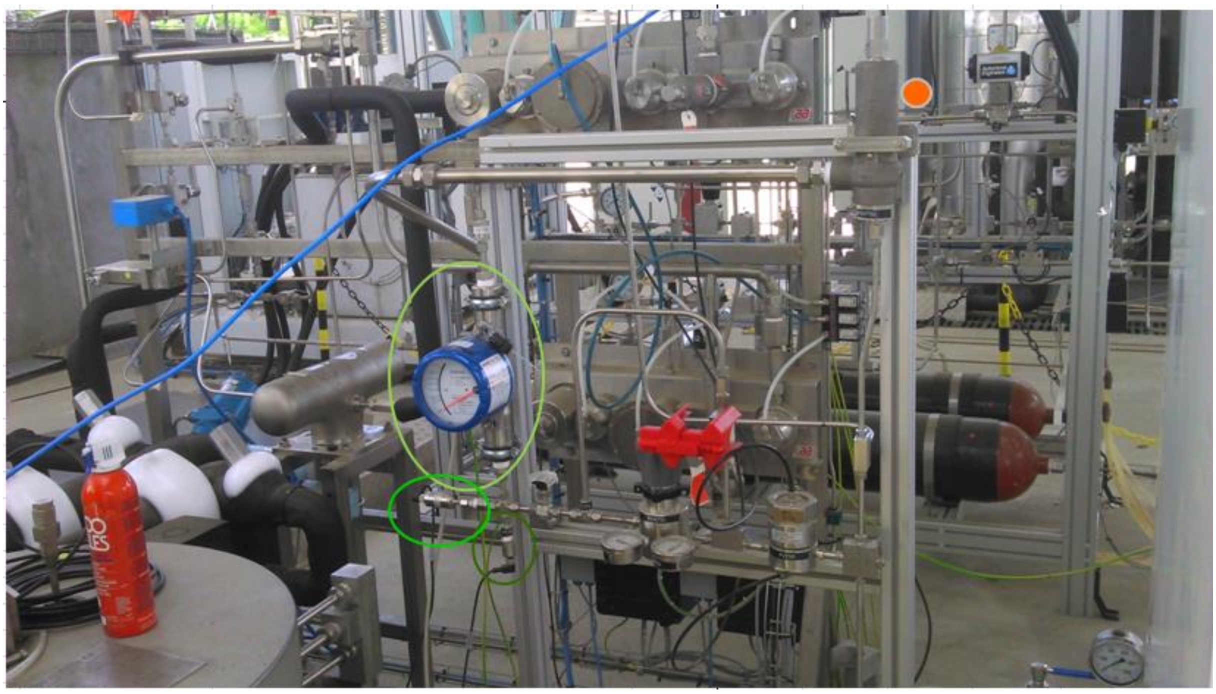


Figure 102: Picture of the equipment positions – Part 2

Table 70: Equipment positions details

Pressure	Approximative value of pipe length			
PT450	C = 475 cm	from the inlet of the tank (0 of the axis)		
PT750	A = 10 cm	from the inlet of the tank (0 of the axis)		
PT751	Rear of the tank, on the thermocouple tree plug			
PT752	F = 225 cm	from the inlet of the tank (0 of the axis)		
Temperature	Approximative value of pipe length			
TT450	B = 415 cm	from the inlet of the tank (0 of the axis)		
TT750	A = 10 cm	from the inlet of the tank (0 of the axis)		
TT751	F = 225 cm	from the inlet of the tank (0 of the axis)		
TT776	X = -70 cm	Y = 120 cm	Z = -60cm	(same axis than the bottle)
TT777	X = 90 cm	Y = 190 cm	Z = -70 cm	(same axis than the bottle)
Mass	Approximative value of pipe length			
FT450	E = 750cm	from the inlet of the tank (0 of the axis)		
FT451	D = 615 cm	from the inlet of the tank (0 of the axis)		
FT452	D = 690 cm	from the inlet of the tank (0 of the axis)		
FT750	G = 240 cm	from the inlet of the tank (0 of the axis)		

Once all sensors were properly connected and identified, different verification steps of calibration were performed. The main calibration was done for the first tests.

For the thermocouples, all the thermocouples were compared to a calibrated device Beamex R-690-0002 scaled on 15/10/2014 for one year. They were all in the range of +/- 1°C error of Type T and +/- 2°C of Type K thermocouples errors. The 2 PT100 sensors used were compared to ambient and factory calibration was taken as reference.

For the pressure sensors (except the defuelling line flowmeter correction sensor), in addition to the factory calibration certificates, a calibration check was performed during the pressure testing under nitrogen as shown in Table 71. PT751 was not tested as the tank was not pressurized, only the lines:

Table 71: Calibration check of pressure sensors

	PT450	PT750
Measurement point 1	1,9 bar	2,4 bar
Measurement point 2	513 bar	511 bar

Nota: it appeared during the testing that PT750 shifted during some experiments, which needed re-adjustment.

The calibration of equipments was followed by a check of all safety functionalities including safety switches and fire protections. The installation was then purged with hydrogen and leak checked.

During hydrogen defuelling of these first tests, the flow orifices and the needle valve on the defuelling line were tested and adjusted to reach the different defuelling flow rates from specified in the test matrix. Additionally some pre-cooling pre-testing and fuelling pressure ramp adjustments were also performed to comply with the test matrix. The pre-cooling tests helped to define the appropriate pre-cooling temperature associated to the heat exchanger and to define a strategy of pre-cooling of the lines before each test. The test started at the beginning of September.

5.4.3 AL-aT test matrix

The test performed at AL-aT were taken out the test matrix presented in previous sections and rearranged to limit the number of cylinder opening and installation modification. The 12 fuelling tests + 4 extra tests and the 7 specified defuellings + 9 not-specified are presented in the following Table 72 and 73:

Table 72: Test matrix in fuelling tests

Fuelling HEX 531 L	Injector diameter	Initial P	Initial T	Inlet gas T	Av. MF	End of fill criterion	Data file name
No injector High flow	10mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 7
No injector Low flow	10mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_1_HEX_500L_ALAT-exp 5

Reference case	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 1
Mass flow rate change	3mm	20 barg	No conditionning	-20°C	2g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 5
Repeatability	3mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 2
Defuelling with 3 pressure steps	3mm	20 barg	No conditionning	-20°C	8 g/s by step	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 8
Initial pressure change	3mm	100 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 3
No cooling + reduced flow	3mm	20 barg	No conditionning	No cooling	2 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 6
Lower pre-cooling	3mm	20 barg	No conditionning	-40°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-SMV-Bank_1_HEX_500L_ALAT-exp 4
Larger injection Ø	6mm	20 barg	No conditionning	-20°C	8 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_1_HEX_500L_ALAT-exp 3
Mass flow rate change + Ø	6mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_1_HEX_500L_ALAT-exp 4
Radial injection	4 x 3mm	20 barg	No conditionning	-20°C	2 g/s	SOC=100% or Tgas>85 °C	Fill-FTD-Bank_1_HEX_500L_ALAT-exp 7
Heterogeneities fast-slow	4 x 3mm	20 barg	No conditionning	-30°C	32g/s then 2.8g/s	SOC=100% or Tgas>85 °C	Fill-Heterogeneities-Bank_1_HEX_500L_ALAT-exp 1
Heterogeneities slow-fast	4 x 3mm	20 barg	No conditionning	-30°C	2.8g/s then 32g/s	SOC=100% or Tgas>85 °C	Fill-Heterogeneities-Bank_1_HEX_500L_ALAT-exp 2
2 high flow tests were performed not specified in the test matrix. As the results are not really relevant, they are not shown here							

Table 73: Test matrix in defuelling tests

Defuelling HEX 500 L	Injector diameter	Initial SOC	Initial T	Av. MF	End of fill criterion	Data file name
No injector	10mm	100%	No conditionning	Constant 2 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 7
Reference case	3mm	100%	No conditionning	Constant 2 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 1
Ramp change Fast - Slow	3mm	100%	No conditionning	8 g/s for 1000s then 1 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 3
Ramp change Slow - Fast	3mm	100%	No conditionning	1 g/s for 6040s then 8 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 4
Lower mass flow rate	3mm	100%	No conditionning	Constant 1 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 6
Repeatability	3mm	100%	No conditionning	Constant 2 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 2
Ramp change High Flow	3mm	100%	No conditionning	15 g/s for 500s then 1 g/s	P < 20 barg or Tgas<-40°C	Defuelling-Bank_1_HEX_500L_ALAT-exp 5

5.4.4 Test results

The tests lasted one month, from the 9th of September to the 16th of October 2015. In the next section, we present the results of each test day per day, with the testing conditions and various parameters. The table 74 to X and the graph from 103 to X give the details of the testing environment and the raw results.

5.4.4.1 Fill SMV n°7 + Defuelling n°7

Table 74: Fill SMV n°7 details

Date	9th September
Afternoon – Fill SMV n°7	17:00 – 17:30
Weather	North wind/ ~25°C ambient
Stabilization duration	all night

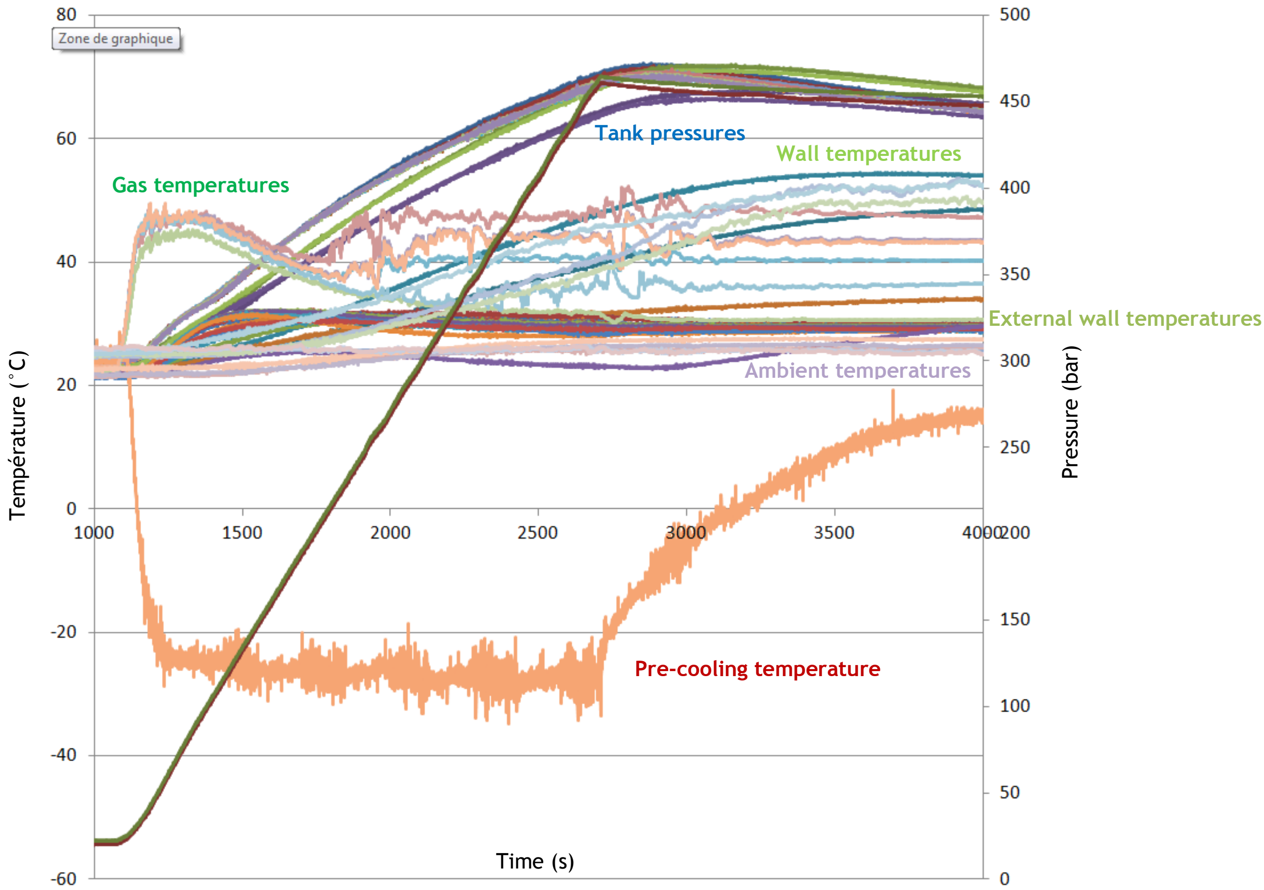


Figure 103: Fill SMV n°7 – 10mm injection Ø

Comments: This test is similar to the reference case, without injector (10mm injection diameter). Maybe due to line temperature difference there was a shift between PT750 and PT751 at the end of fill. The fuelling ramp rate was around 0,3 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -26°C. As there are only five thermocouples in the back of the tank, it is more difficult to get a clear picture of temperature behaviours without simulations. We can however observe a small stratification in the back of the tank, and indirectly between the front and the back of the tank, through liner/composite wall measurements.

Table 75: Defuelling n°7 details

Date	10th September
Morning – Defuelling n°7	9:10 – 11:00
Weather	South wind / ~15°C ambient
Stabilization duration	5 h 00 min

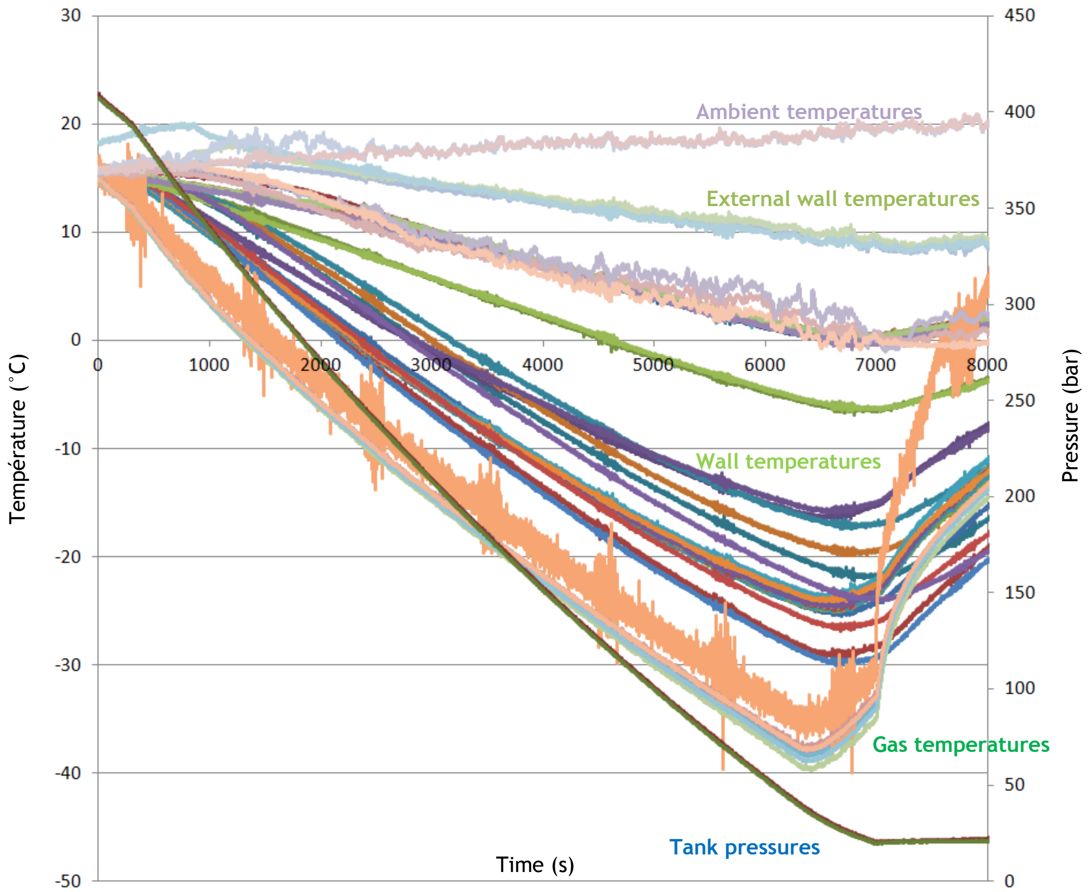


Figure 104: Defuelling n°7 – 10mm injection Ø

Comments: this test is similar to the reference case but with a larger injection diameter. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 406 bar, 15°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. It seems that for defuelling the lowest temperatures are in the back of the tank and the gas temperature is colder than the wall temperatures.

5.4.4.2 Fill FTD n°5+ Defuelling n°7 bis

Table 76: Fill FTD n°5 details

Date	10th September
Afternoon – Fill FTD n°5	16:15 – 18:00
Weather	Slight north wind / ~23°C ambient
Stabilization duration	All night

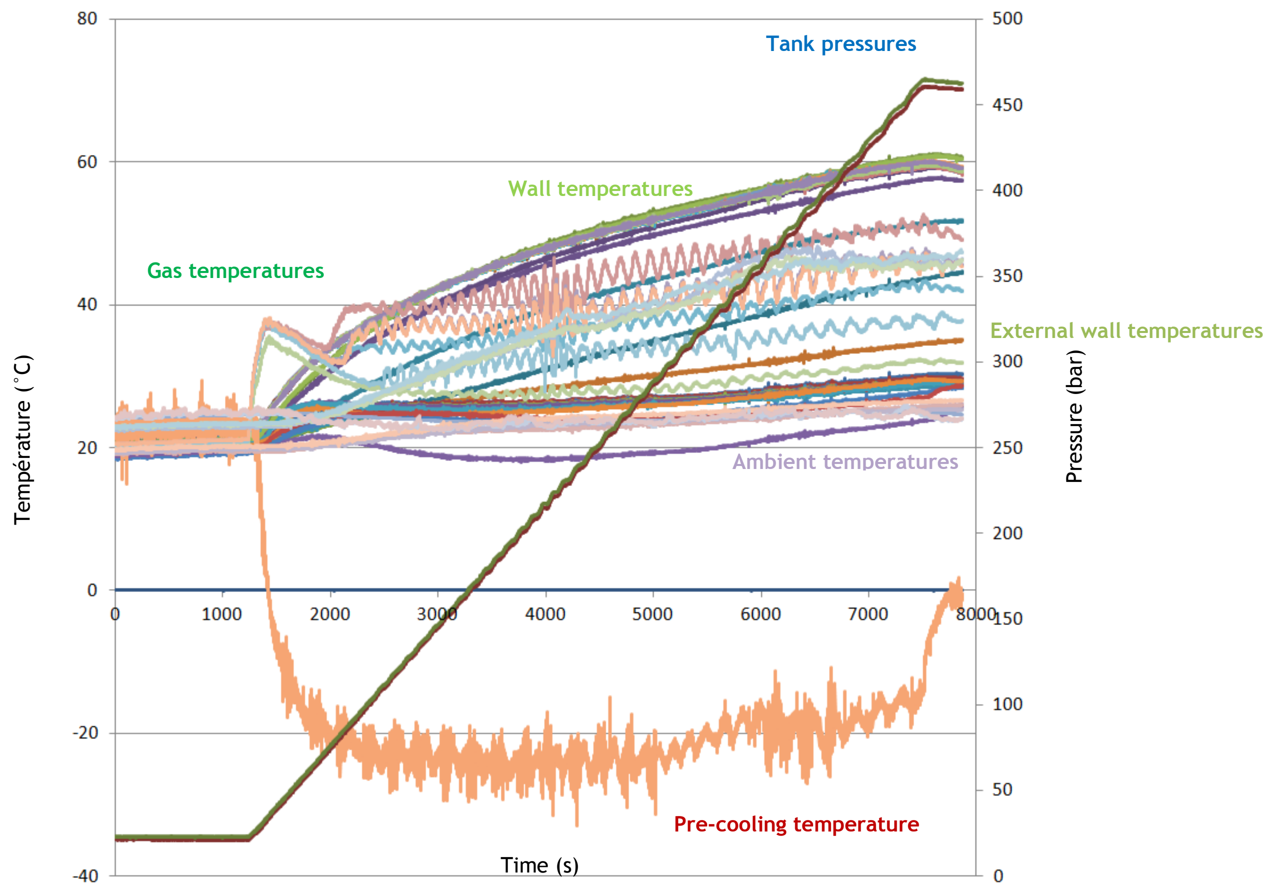


Figure 105: Fill FTD n°5 - 10mm injection Ø + low flow rate

Comments: This test is similar to the previous case, without injector (10mm injection diameter) and at lower flowrate. Maybe due to line temperature difference there was a shift between PT750 and PT751 at the end of fill. The fuelling ramp rate was around 0,1 bar/s, which created some fluctuations due to regulations controls on such a huge tank and the fuelling was stopped on a pressure condition. The pre-cooling reaches -25°C. As there are only five thermocouples in the back of the tank, it is more difficult to get a clear picture of temperature behaviours without simulations. We can however observe a small stratification in the back of the tank, and indirectly between the front and the back of the tank, through liner/composite wall measurements. The results are close to the previous test results.

Table 77: Defuelling n°7 bis details

Date	11th September
Morning – Defuelling n°7	07:15 – 09:00
Weather	South wind / ~15°C ambient
Stabilization duration	5 h 10 min

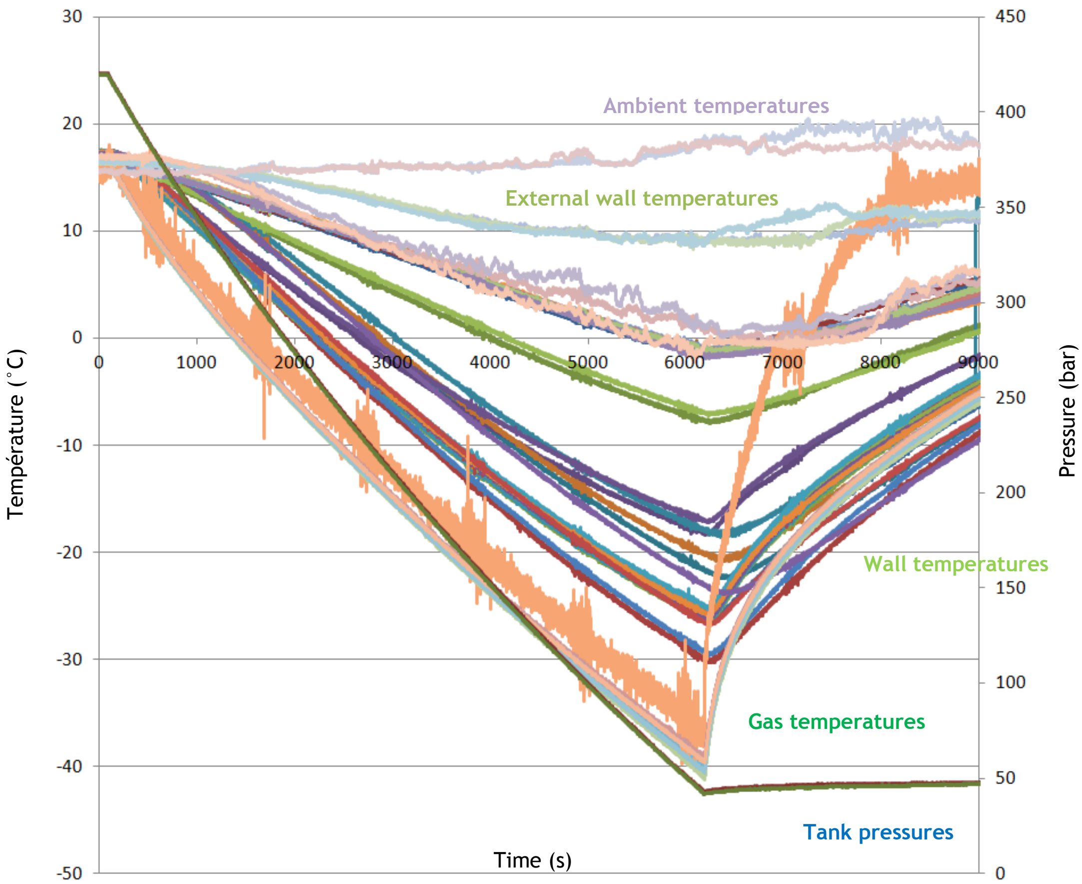


Figure 106: Defuelling n°7 bis - 10mm injection Ø

Comments: this test is a repetition of previous defuelling as there was no specific test defined here. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 419 bar, 15°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. It seems that for defuelling the lowest temperatures are in the back of the tank and the gas temperature is colder than the wall temperatures.

The reproducibility with previous test is good, same behaviours and similar final values. Following this test, the tank was completely defuelled, purged with nitrogen. After that the 3mm injector was installed and the tank prepared at 20 bar for the next day. TT750 inlet temperature which had a lot of noise was also replaced.

5.4.4.3 Fill SMV n°1+ Defuelling n°1

Table 78: Fill SMV n°1 details

Date	15th September
Afternoon – Fill SMV n°1	16:50 – 17:30
Weather	No wind / ~19°C ambient
Stabilization duration	All night

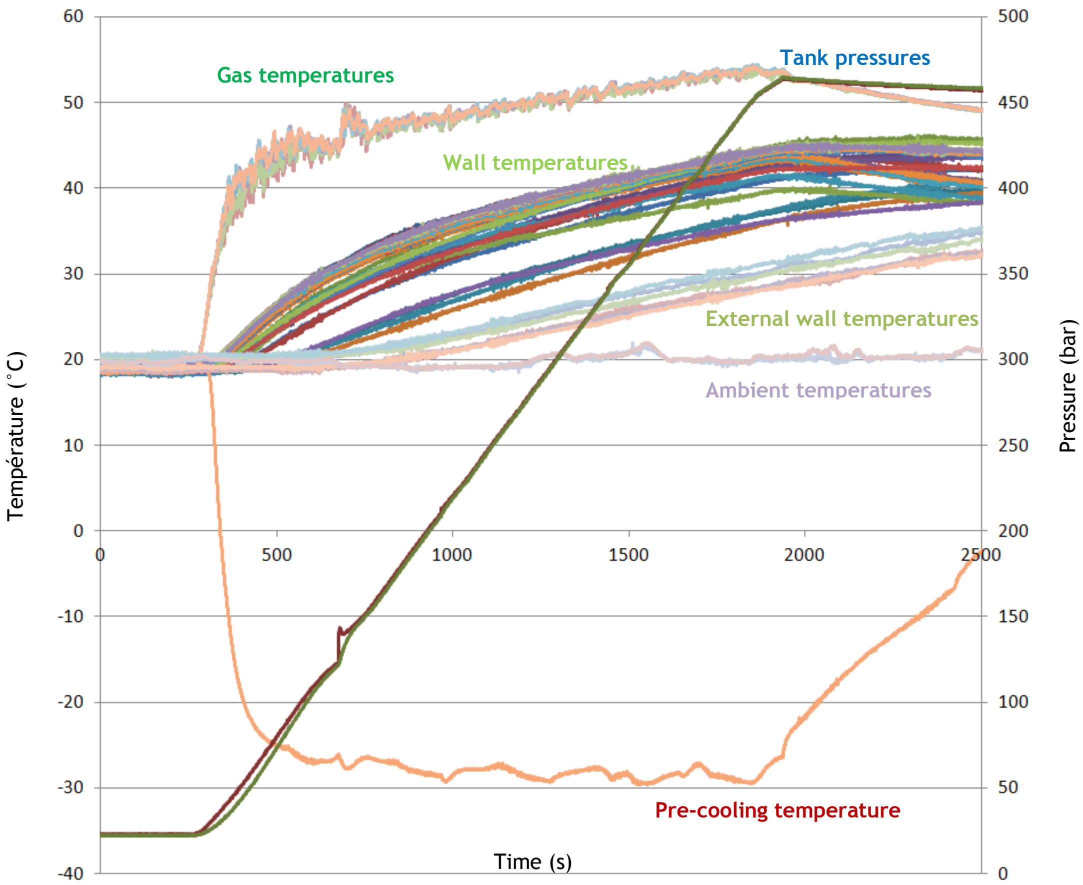


Figure 107: Fill SMV n°1 - reference case

Comments: this is the reference case with an average flow rate of 8 g/s, a pre-cooling at -20°C, no conditioning, 3mm injection diameter and an initial pressure of 20 bar. The fuelling ramp rate was around 0,3 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -27°C. In this case we observe no temperature stratification and thus the gas, wall and external wall temperatures stay separated. We see as with the small tank that a smaller diameter and a higher flow rate are reducing the stratification effect.

Table 79: Defuelling n°1 details

Date	16th September
Morning – Defuelling n°1	8:20 – 10:15
Weather	Strong south wind / ~24°C ambient
Stabilization duration	5 h 10 min

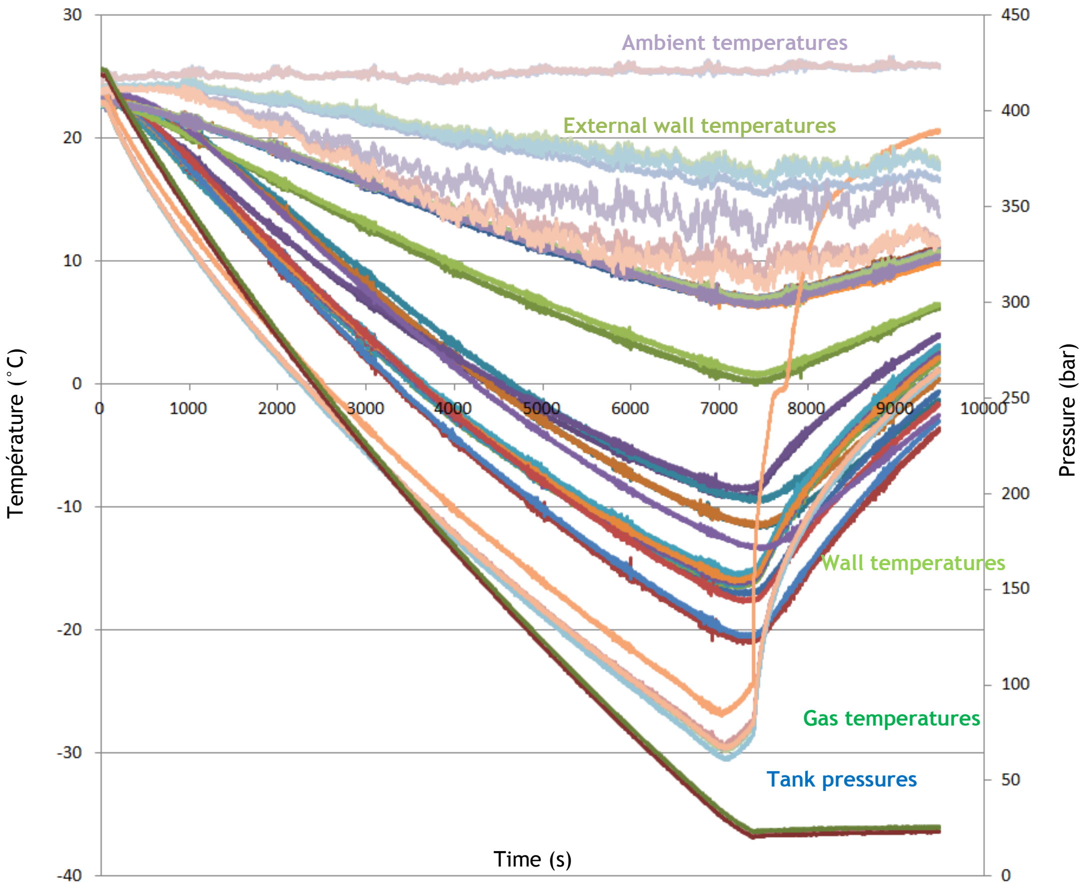


Figure 108: Defuelling n°1 – reference case

Comments: this is the reference case with a defuelling flow rate of 2 g/s, 3mm injection diameter, no conditioning, an initial SOC around 100%. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 421 bar, 24°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. A first analysis shows a limited impact of the injection diameters. The temperature shift compared to the 10 mm injection diameter corresponds to the ambient temperature difference.

5.4.4.4 Fill SMV n°5+ Defuelling n°3

Table 80: Fill SMV n°5 details

Date	16th September
Afternoon – Fill SMV n°5	16:55 – 18:40
Weather	Strong south wind / ~28°C ambient
Stabilization duration	All night

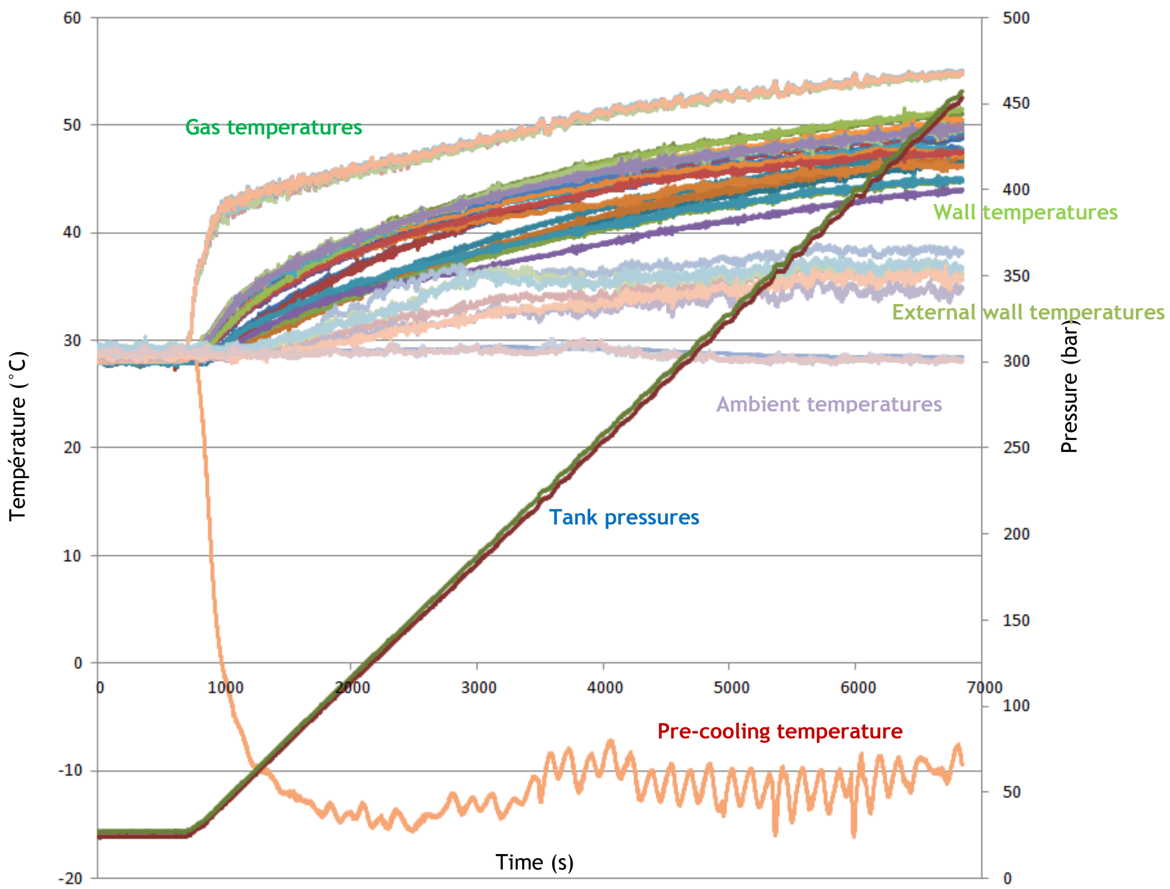


Figure 109: Fill SMV n°5 - lower flowrate

Comments: this test has a lower flowrate than the reference case, to identify the impact of this parameter. The fuelling ramp rate was around 0,01 bar/s, creating some fluctuations in the ramp control and the fuelling was stopped on a pressure condition. The pre-cooling reaches -11°C, higher than specified. In this case we would expect some temperature stratification that does not occur; the injection diameter probably limits the stratification effect. In this case the low flowrate reduces the maximum temperatures reached.

Table 81: Defuelling n°3 details

Date	17th September
Morning - Defuelling n°3	8:45 - 10:45
Weather	Strong north wind/ Stormy / ~14°C ambient
Stabilization duration	5 h 50 min

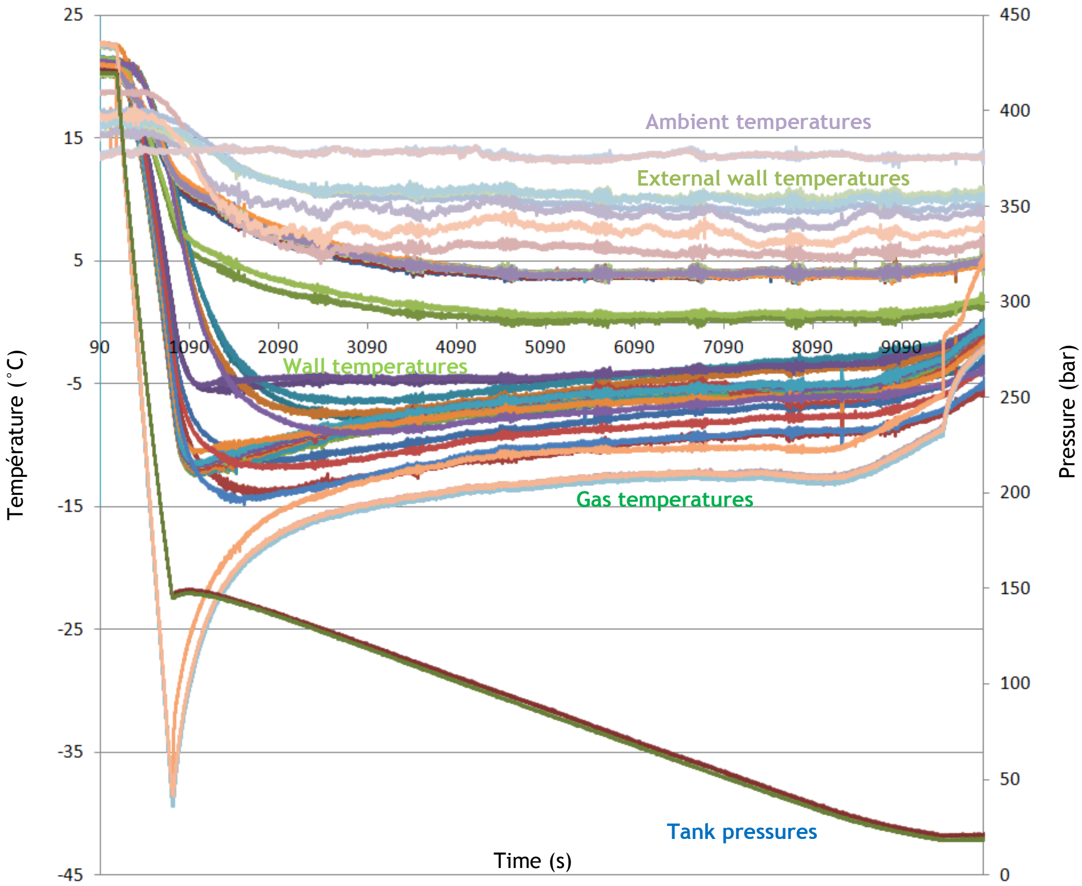


Figure 110: Defuelling n°3 - flowrate profile

Comments: this is a test with faster flowrate ramp at the beginning, around 8 g/s for 700s followed by the rest at 1 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 421 bar, 21°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling strategy looks efficient, by strongly decreasing the pressure and almost reaching the tank limit temperature, then a slower flowrate brings back all temperatures in a more acceptable range.

5.4.4.5 Fill SMV n°2+ Defuelling n°4

Table 82: Fill SMV n°2 details

Date	17th September
Afternoon – Fill SMV n°2	16:40 – 17:07
Weather	No wind / calm weather / ~18°C ambient
Stabilization duration	All night

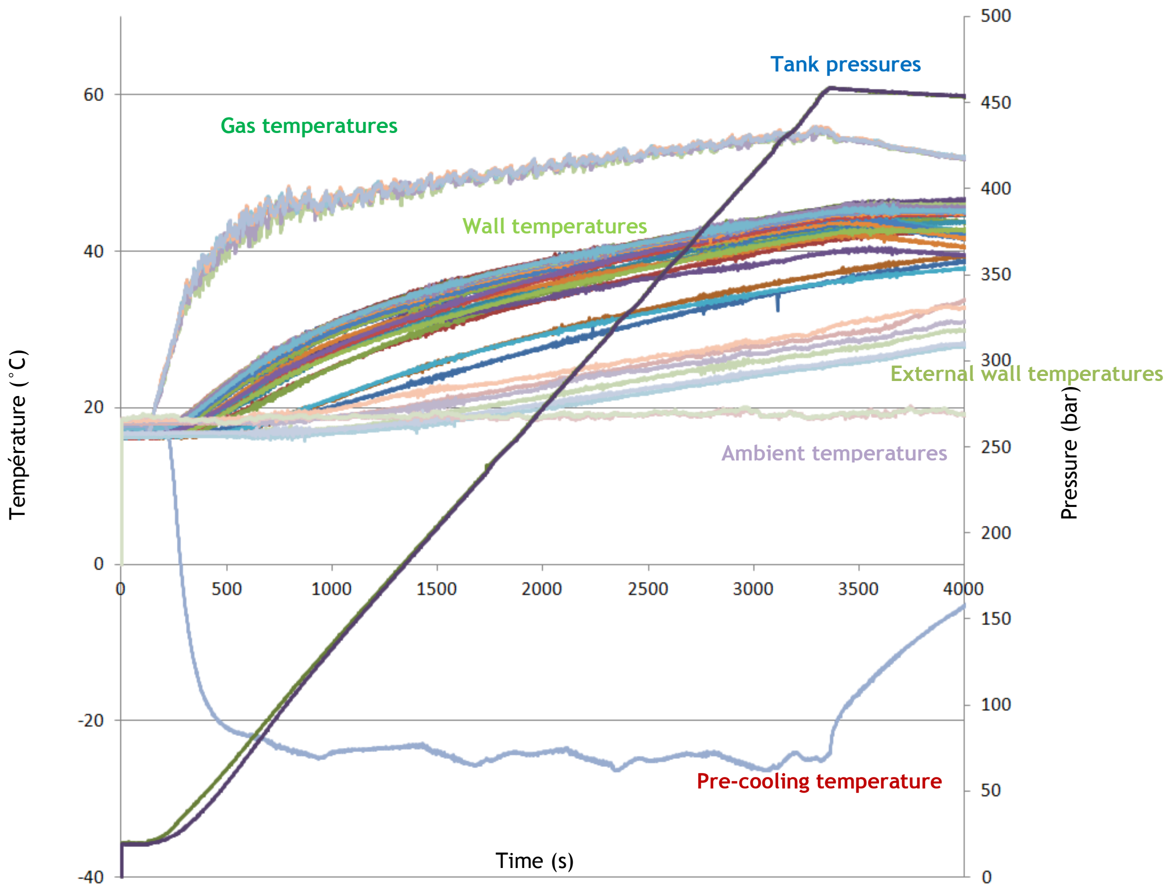


Figure 111: Fill SMV n°2 - repeatability

Comments: this is the repeatability of the reference case with an average flow rate of 8 g/s, a pre-cooling at -20°C, no conditioning, 3mm injection diameter and an initial pressure of 20 bar. The fuelling ramp rate was around 0,3 bar/s and the fuelling was stopped on a pressure condition. The pre-cooling reaches -25°C. In this case we observe no temperature stratification and thus the gas, wall and external wall temperatures stay separated. The repeatability is good.

Table 83: Defuelling n°4 details

Date	18th September
Morning - Defuelling n°4	08:44 - 10:24
Weather	Slight north wind / Slight rain/ ~14°C ambient
Stabilization duration	06h 20min

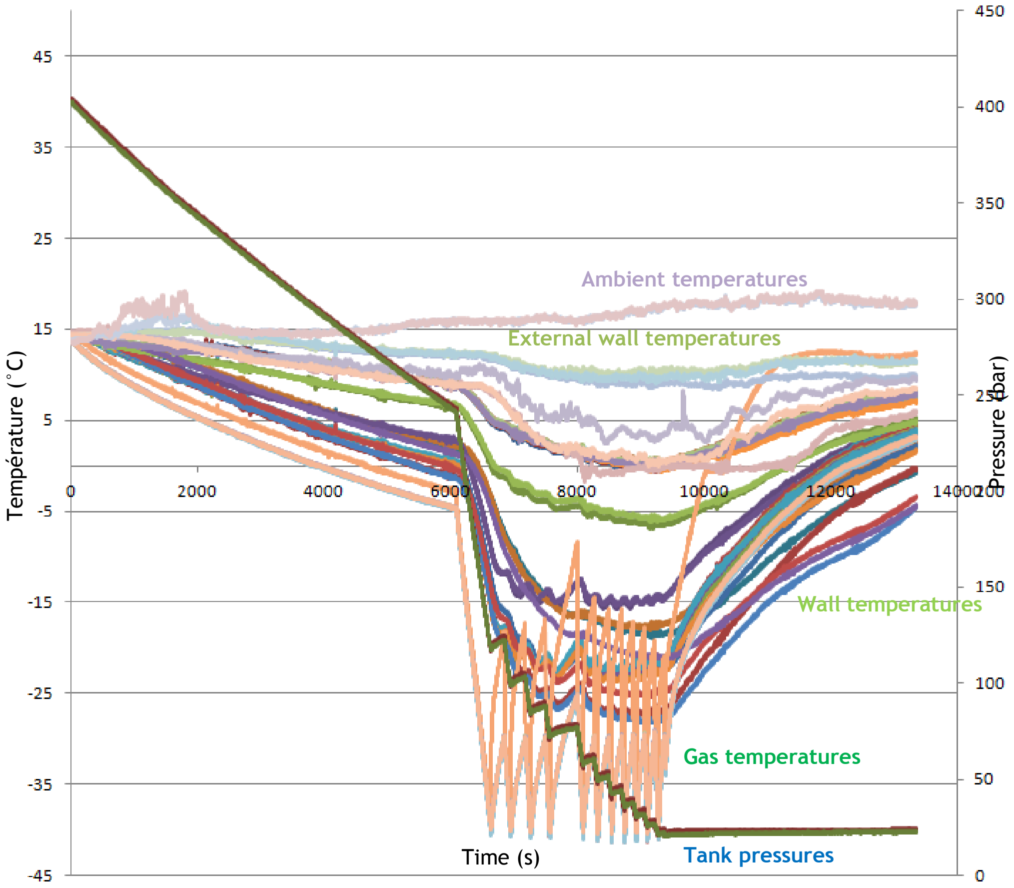


Figure 112: Defuelling n°4 - flowrate profile

Comments: this is a test with slower flowrate ramp at the beginning, around 1 g/s for 6040s followed by the rest at 8 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 402 bar, 14°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling strategy looks less efficient, than fast then slow. As we can see the ramp increase led to the limit temperature and a defuelling stop that was restarted several times.

5.4.4.6 Fill SMV n°8+ Defuelling n°6

Table 84: Fill SMV n°8 details

Date	18th September
Afternoon – Fill SMV n°8	In 4 steps 16:45 – 17:35
Weather	Slight northwind / Sun on the back of the tank / ~21°C ambient
Stabilization duration	All night

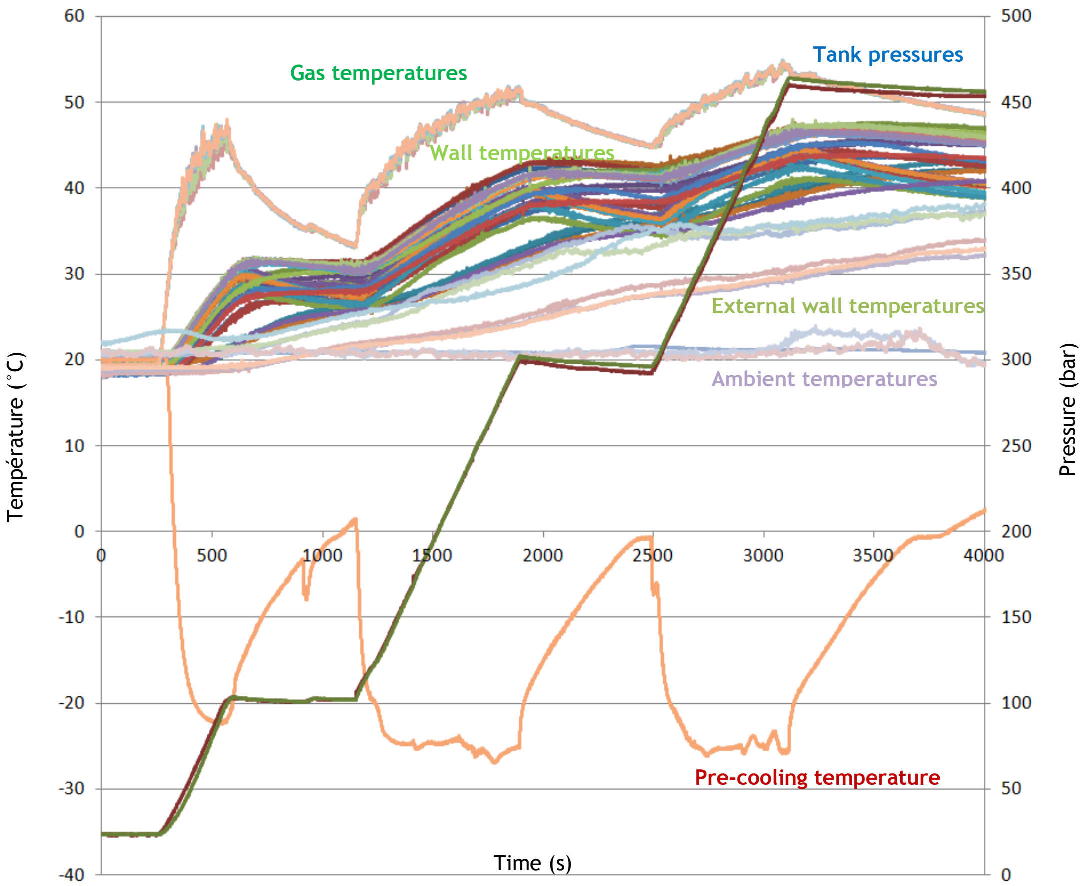


Figure 113: Fill SMV n°8 – pressure profile

Comments: this is a test with a pressure profile, with stops within the fuelling. The fuelling ramp rate was around 0,3 bar/s and the fuelling was stopped on 3 pressure targets. The pre-cooling hardly reaches -24°C during the fuelling phases. We can see for each step the temperature increase followed by a stabilisation. We observe the short transition period of the gas temperature elevation.

Table 85: Defuelling n°6 details

Date	19th September
Morning - Defuelling n°6	11:25 - 15:40
Weather	Slight north wind / calm weather/ ~17°C ambient
Stabilization duration	Two days

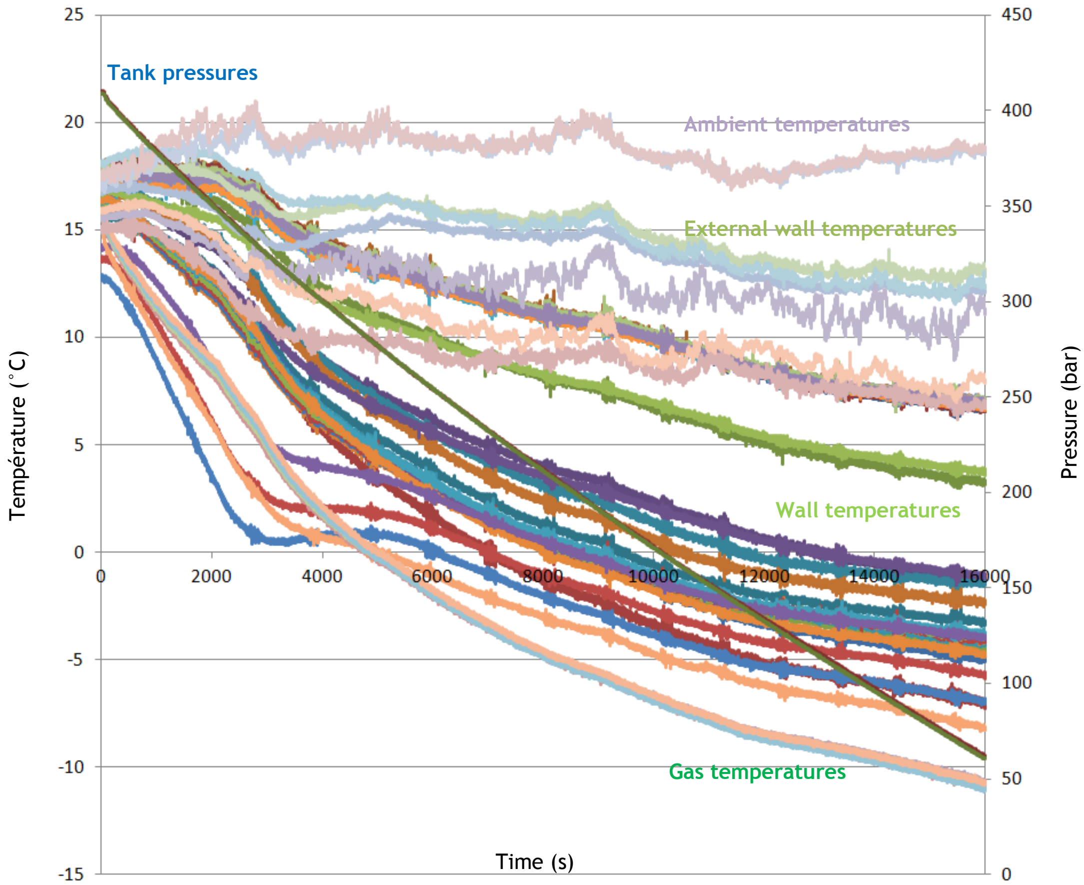


Figure 114: Defuelling n°6 - lower flowrate

Comments: this is a test with slower flowrate ramp around 1 g/s The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 409 bar, 17°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling reaches higher final temperatures as the defuelling time was longer.

5.4.4.7 Fill SMV n°3+ Defuelling n°2

Table 86: Fill SMV n°3 details

Date	21st September
Afternoon – Fill SMV n°3	16:50 – 17:10
Weather	North wind /Sun on the tank side / ~21°C ambient
Stabilization duration	All night

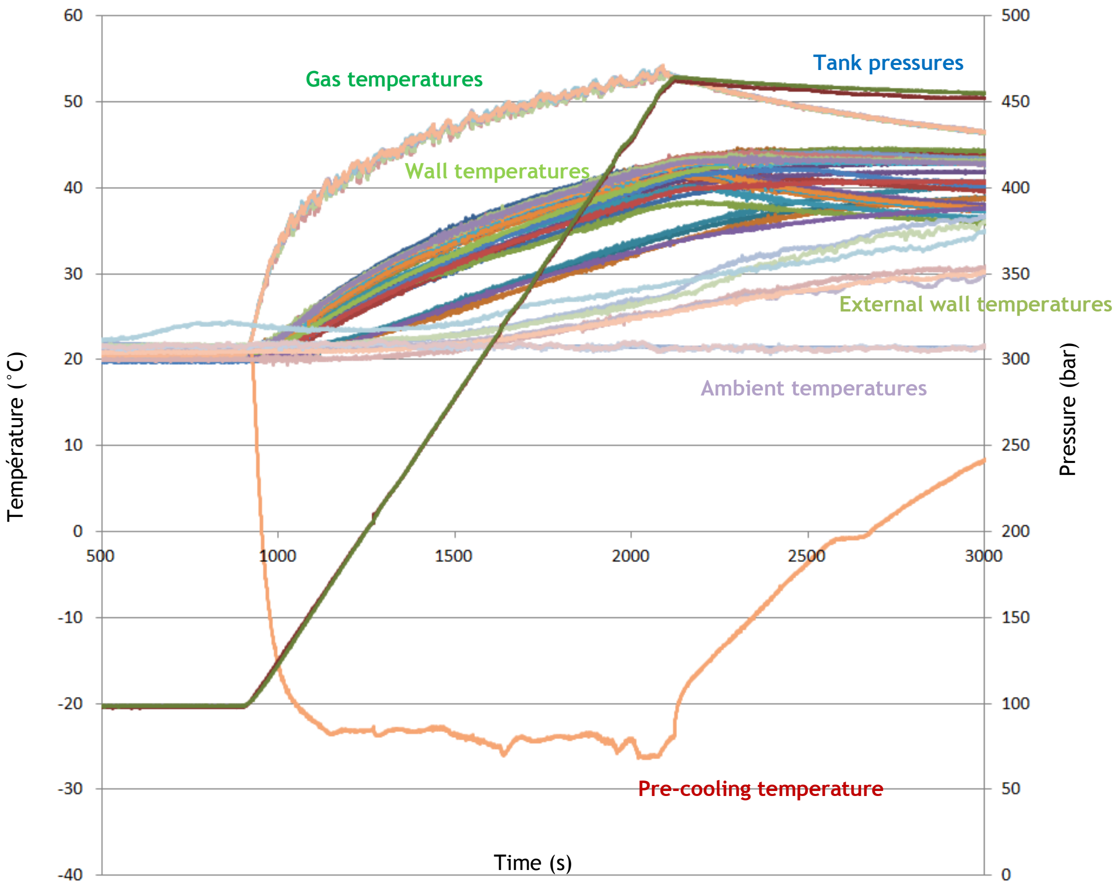


Figure 115: Fill SMV n°3 – higher initial pressure

Comments: this is a test with a higher initial pressure. The fuelling ramp rate was around 0,3 bar/s and it stopped on a pressure condition. The pre-cooling reaches -24°C. We don't see any stratification and we can on a first observation confirm that a higher initial pressure reduces the maximum final temperatures.

Table 87: Defuelling n°2 details

Date	22^{nd} September
Morning - Defuelling n°2	08:30 – 10:30
Weather	Almost no wind / ~12°C ambient
Stabilization duration	6 h 50 min

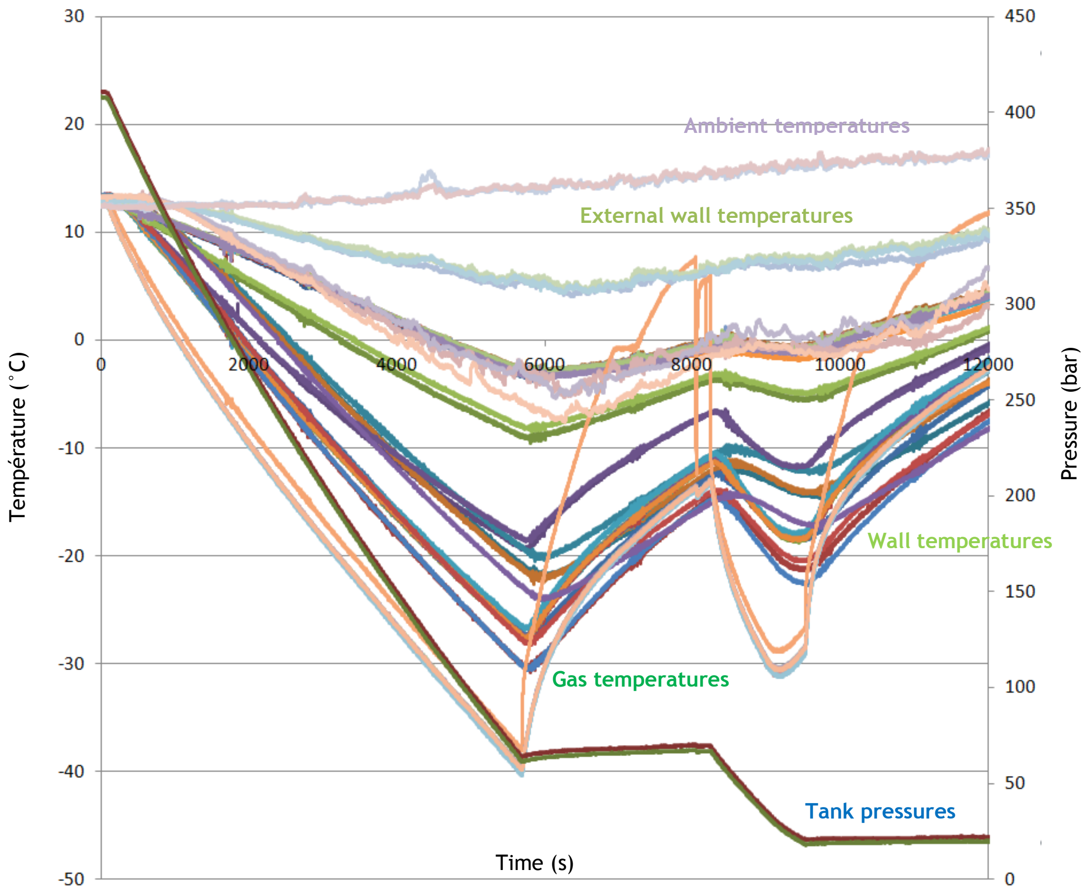


Figure 116: Defuelling n°2 - repeatability

Comments: this is the repeatability of the reference case. The defuelling started with an ambient / gas average temperature difference of ~ 2°C. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 407 bar, 12°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. In this case we reached the minimum temperatures which stopped the defuelling that needed to be restarted. In this state it can't be compared properly as a raw data with the reference case

5.4.4.8 Fill SMV n°6 + Defuelling n°5

Table 88: Fill SMV n°6 details

Date	22nd September
Afternoon – Fill SMV n°6	17:20 – 19:05
Weather	North wind / cloudy / ~20°C ambient
Stabilization duration	All night

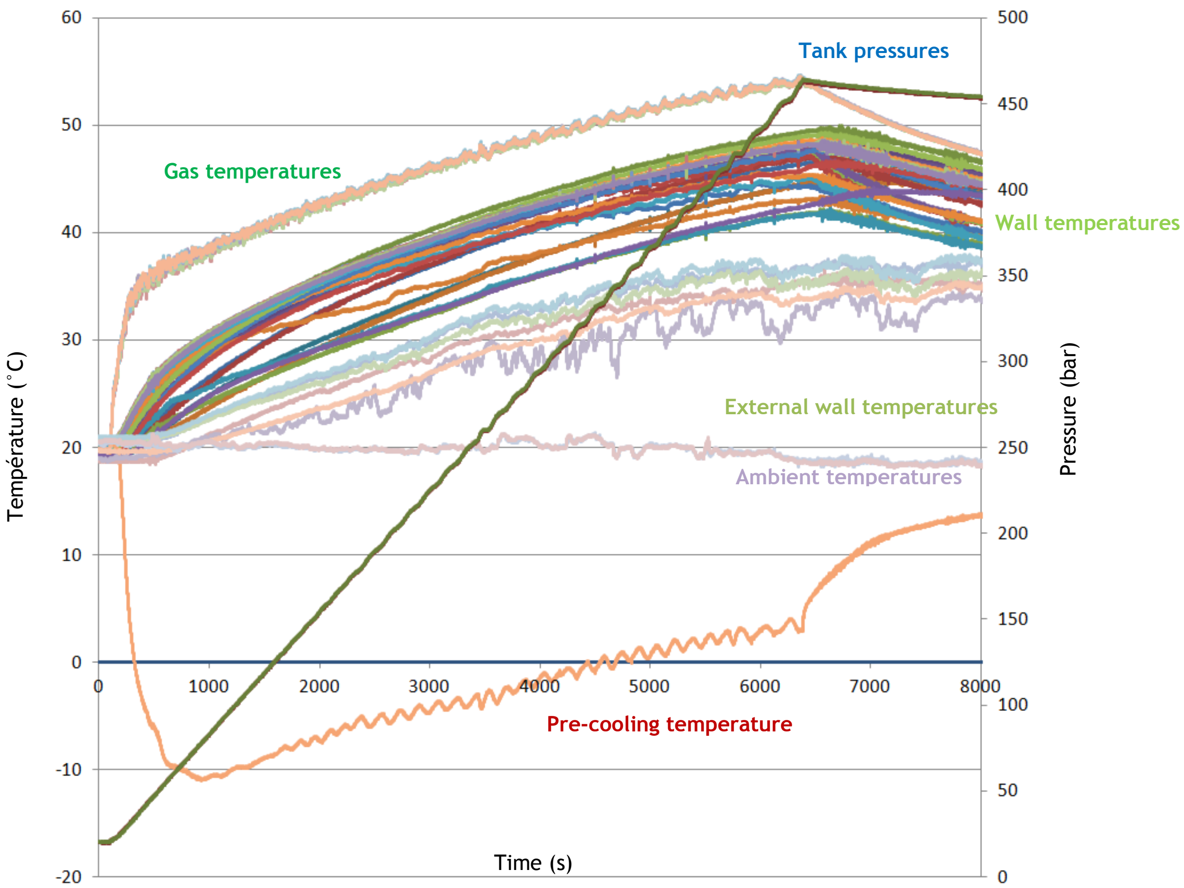


Figure 117: Fill SMV n°6 - no pre-cooling

Comments: this is a test with no pre-cooling, to evaluate the impact of non pre-cooled fuellings. The pre-cooling was set to obtain an average around 0°C, which is not exactly the case. The fuelling ramp rate was around 0,1 bar/s and it stopped on a pressure condition. The pre-cooling is reaches -5°C. We don't see any stratification but the gas temperature is only taken in the back. The parameters variations are too important to simply identify the impact of pre-cooling without additional simulations

Table 89: Defuelling n°5 details

Date	23rd September
Morning - Defuelling n°5	08:14 – 13:55
Weather	Slight north wind / rainy / ~10°C ambient
Stabilization duration	5h50

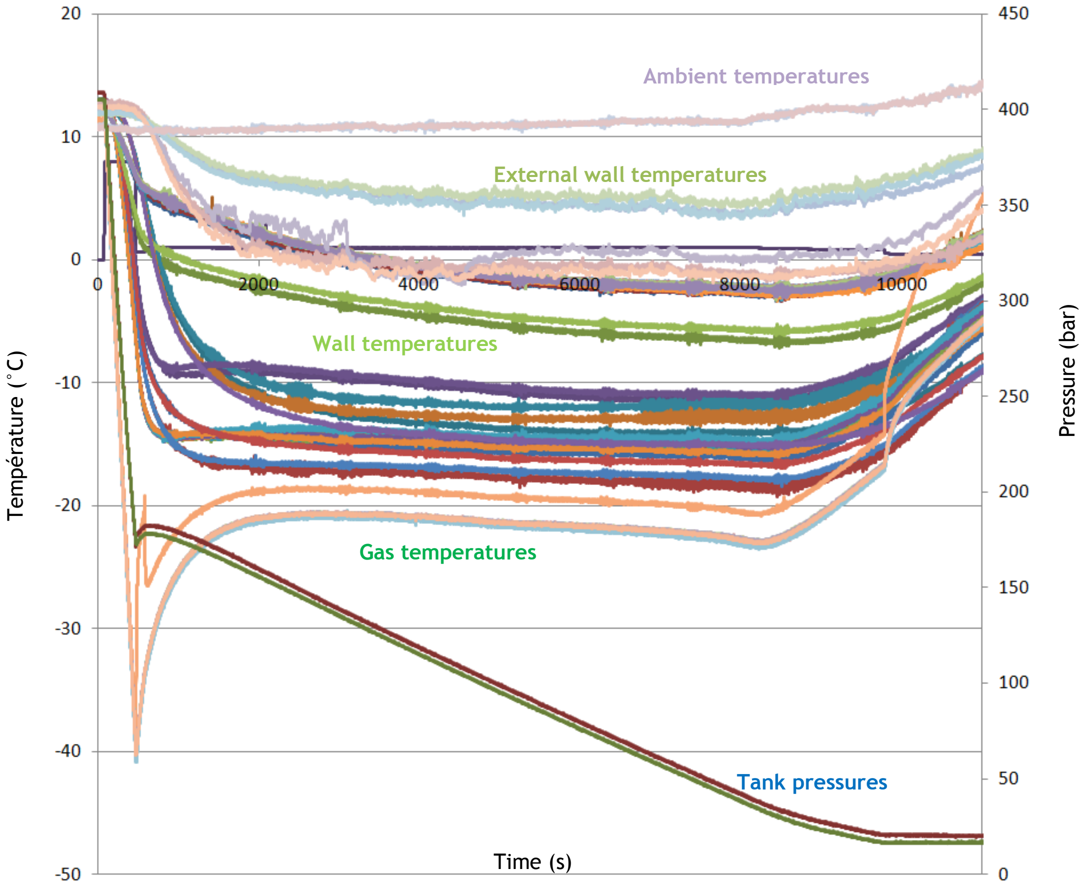


Figure 118: Defuelling n°5 – flowrate variation

Comments: this is a test with faster flowrate ramp at the beginning, around 15 g/s for 500s followed by the rest at 1 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 405 bar, 12°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This test confirms the efficiency of the defuelling strategy, by strongly decreasing the pressure and almost reaching the tank limit temperature, then a slower flowrate brings back all temperatures in a more acceptable range. In this case the first defuelling rate led to temperature below the tank limit and thus a defuelling stop. It had to be restarted

5.4.4.9 Fill SMV n°4+ Defuelling n°3bis

Table 90: Fill SMV n°4 details

Date	23rd September
Afternoon- Fill SMV n°4	16:50 – 17:20
Weather	North wind / ~15°C ambient
Stabilization duration	All night

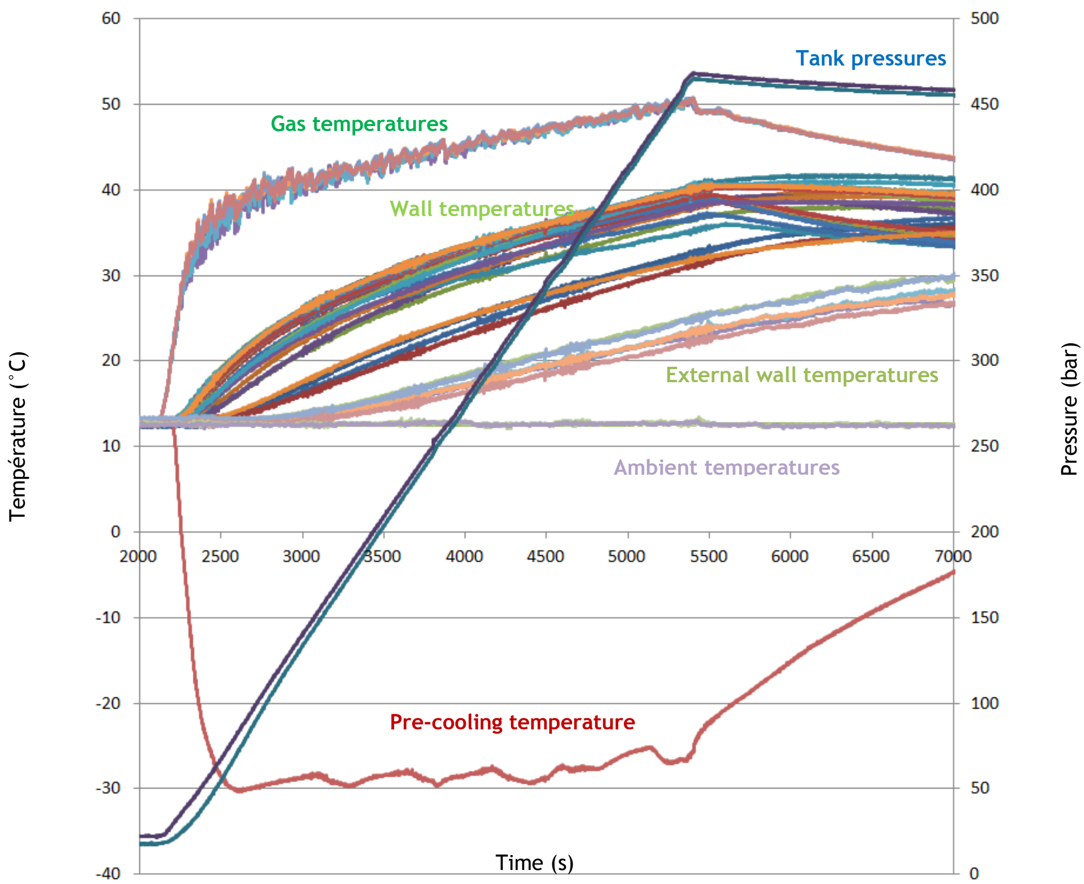


Figure 119: Fill SMV n°4 – lower pre-cooling

Comments: this is a test with a lower pre-cooling, to evaluate the impact of an increased pre-cooling. The fuelling ramp rate was around 0,3 bar/s and it stopped on a pressure condition. The pre-cooling reaches -30°C. There is no stratification in the back of tank and it seems limited in the rest of the tank. The pre-cooling impact can be seen on lower end of fill temperatures

Table 91: Defuelling n°3 bis details

Date	24th September
Morning - Defuelling n°3 bis	08:48 - 09:05
Weather	No wind / Sun on the tank rear /Winter sunny morning / ~9°C ambient
Stabilization duration	3 h 00

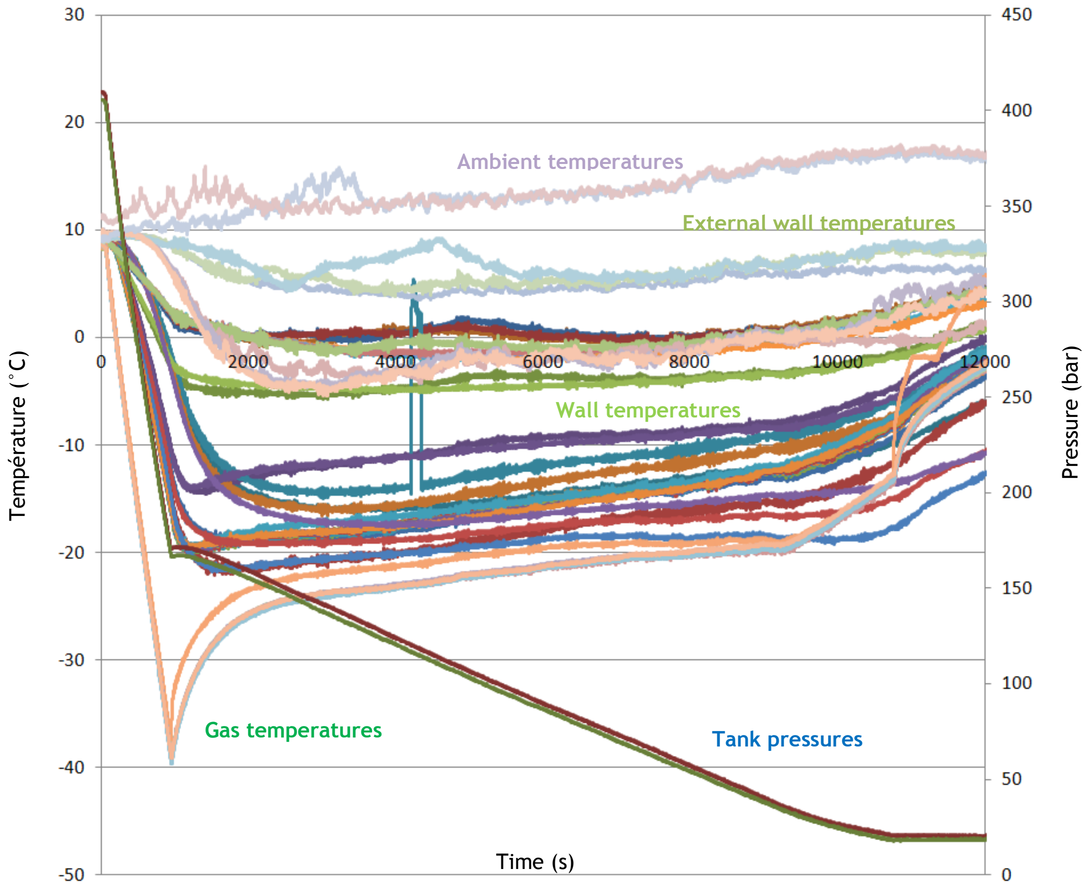


Figure 120: Defuelling n°3 bis - repeatability

Comments: : this is a test is a repetition of n°3, with faster flowrate ramp at the beginning, around 8 g/s for 700s followed by the rest at 1 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 405 bar, 9°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling strategy looks efficient, by strongly decreasing the pressure and almost reaching the tank limit temperature, then a slower flowrate brings back all temperatures in a more acceptable range. The results are consistant with the first Defuelling n°3.

Following this test, the tank was completely defuelled, purged with nitrogen. After that the 6mm injector replaced the 3mm injector and the tank was prepared at 20 bar for the next test.

5.4.4.10 Fill FTD n°3+ Defuelling n°6 bis

Table 92: Fill FTD n°3 details

Date	06th October
Afternoon – Fill FTD n°3	17:10 – 17:40
Weather	No wind / rain / ~16°C ambient
Stabilization duration	All night

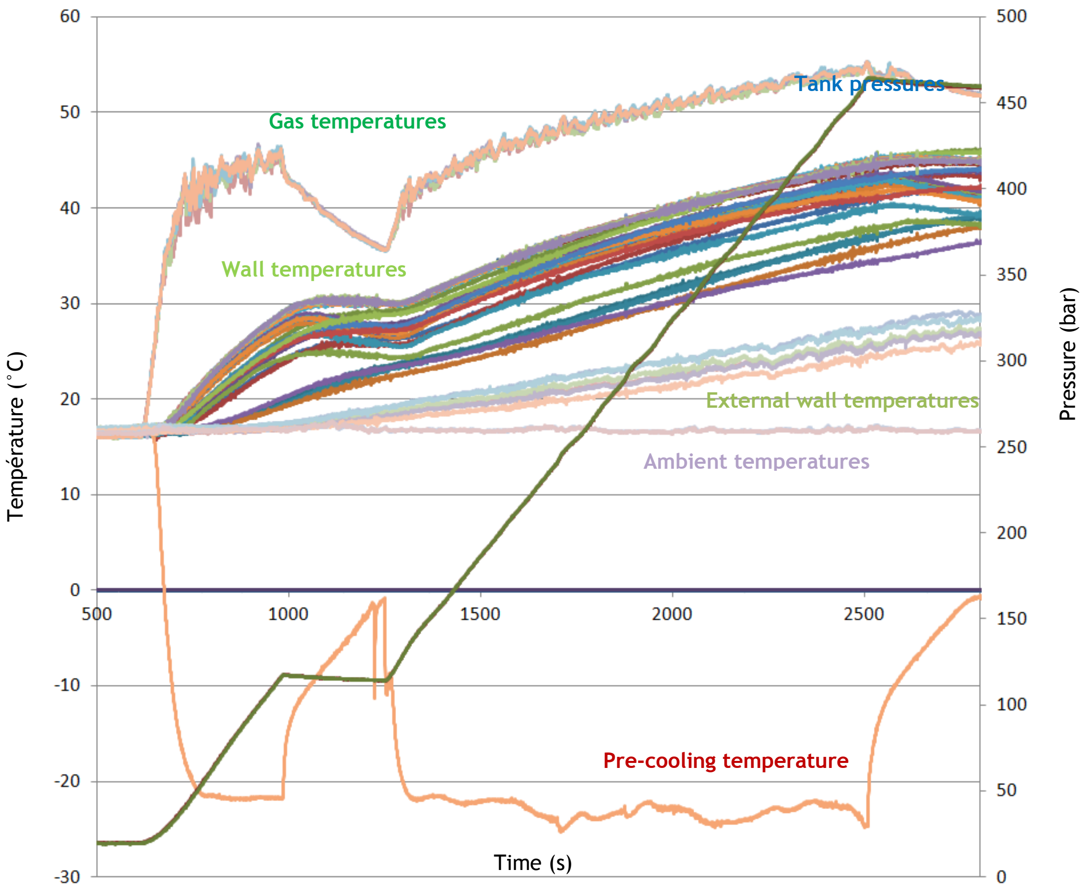


Figure 121: Fill FTD n°3 – 6mm injection diameter

Comments: this test is the reference case with a 6mm injection diameter, performed to evaluate the impact of the injection diameter. The fuelling ramp rate was around 0,3 bar/s and it stopped on a pressure condition. The pre-cooling reaches -21°C. Due to a fault, the fuelling was done in two steps. We can't really identify stratification from the raw data and the impact of the injection diameter.

Table 93: Defuelling n°6 bis details

Date	07th October
Morning - Defuelling n°6 bis	08:00 – 12:00
Weather	North wind / rainy / ~13°C ambient
Stabilization duration	6 h 00 min

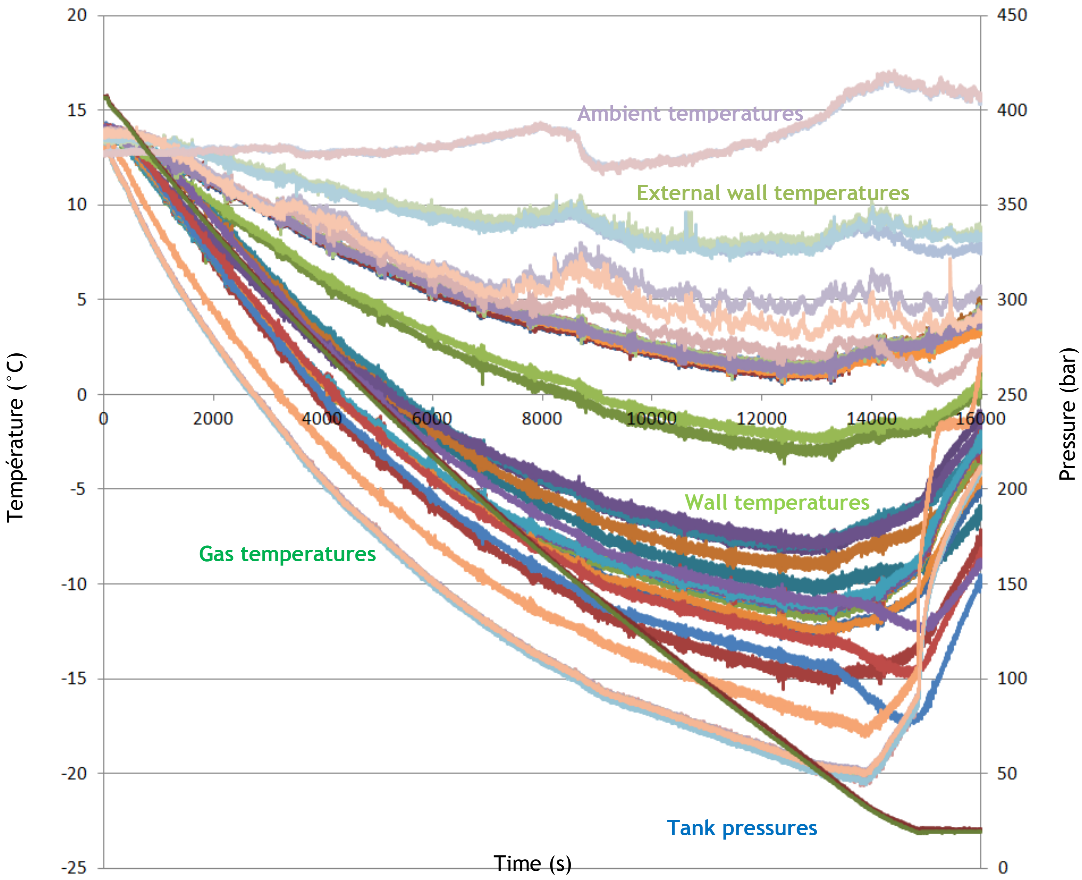


Figure 122: Defuelling n°6 bis – 6mm injector slow defuelling

Comments: this is a test with slower flowrate ramp around 1 g/s The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 407 bar, 13°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling reaches higher final temperatures as the defuelling time was longer. This test seems to reach lower temperatures than the 3mm injector similar test, but no clear conclusions on the impact of the injector diameter comes out here.

5.4.4.11 Fill FTD n°4+ Defuelling n°3 bis

Table 94: Fill FTD n°4 details

Date	07th October
Afternoon – Fill FTD n°4	18:00 – 20:00
Weather	Strong north wind /Cloudy/ ~15°C ambient
Stabilization duration	All night

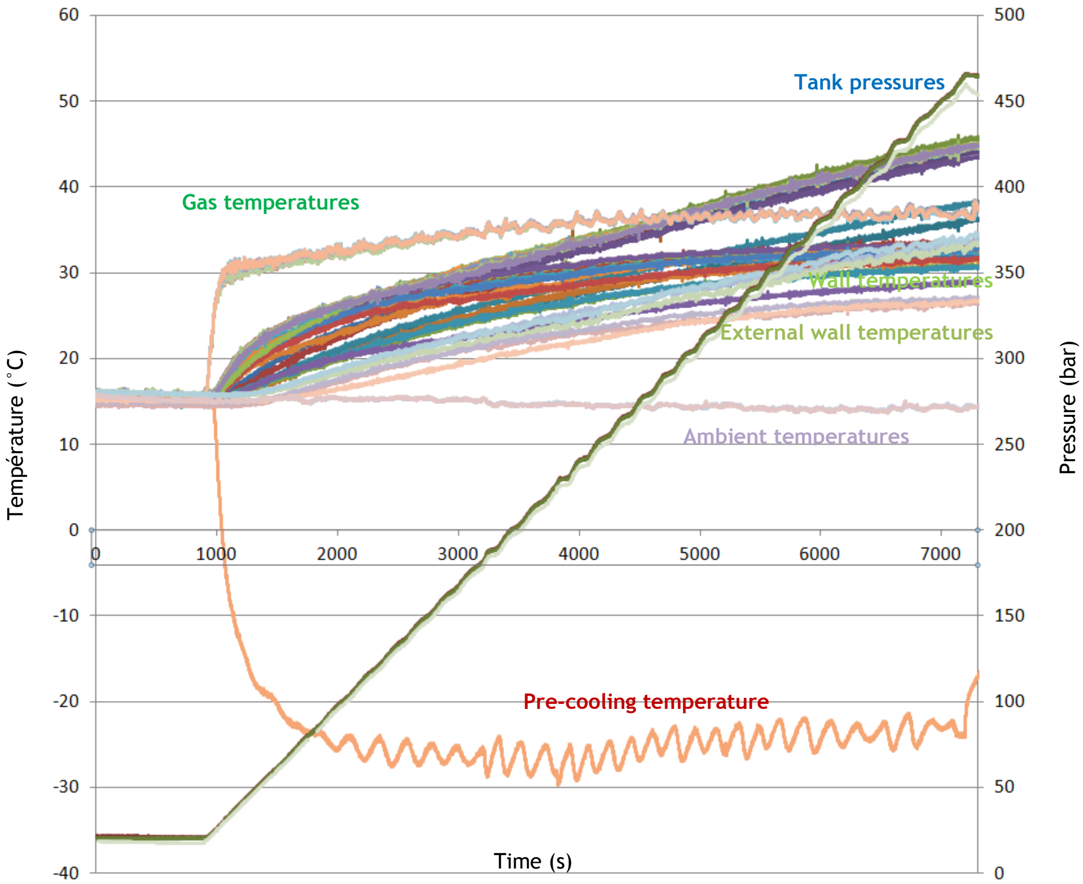


Figure 123: Fill FTD n°4 – 6mm injector slower flowrate

Comments: this test is performed at the low flowrate with a 6mm diameter injector, to compare it with the case with the 3mm diameter injector. The fuelling ramp rate was around 0,1 bar/s and it stopped on a pressure condition. The pre-cooling reaches -25°C. Stratification appears clearly, not in the back of the tank, but indirectly through the wall sensors, showing that the lower flowrate increases the stratification effect.

Table 95: Defuelling n°3 bis details

Date	08th October
Morning - Defuelling n°3 bis	09:10 – 12:10
Weather	No wind / No sun on the tank / ~9°C ambient
Stabilization duration	4h 50 min

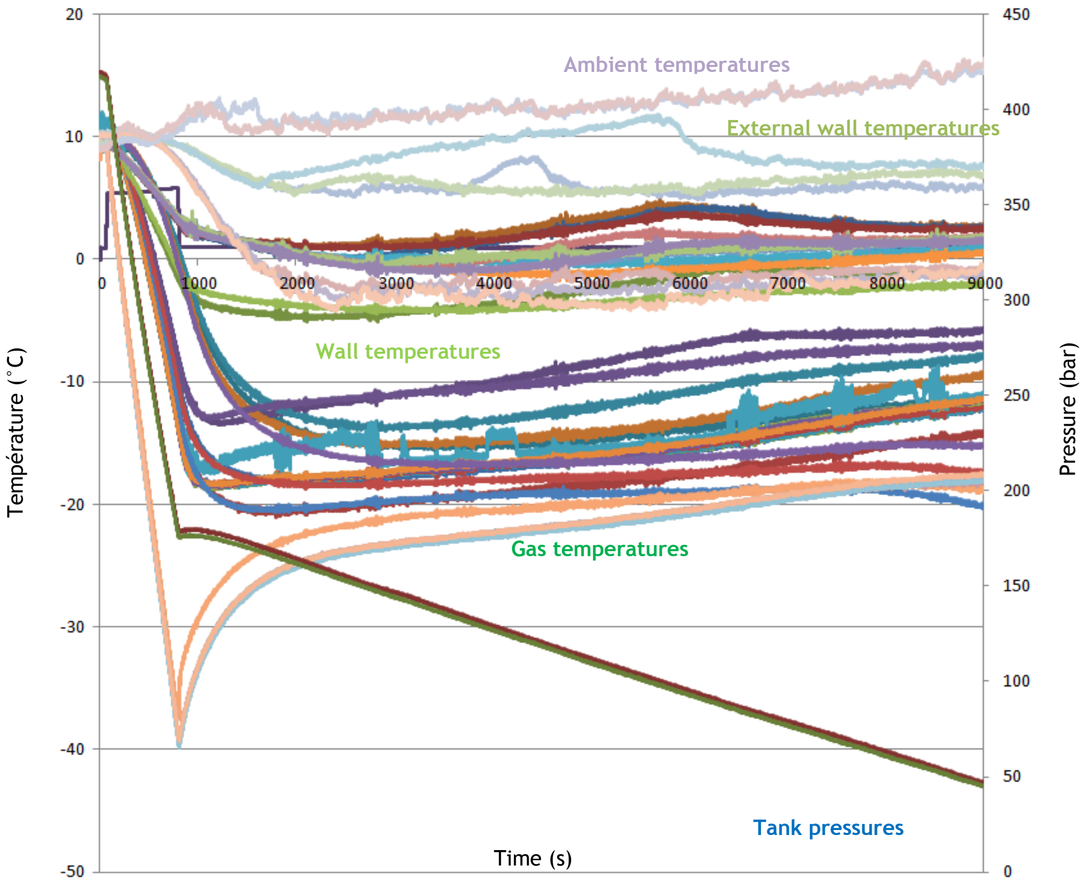


Figure 124: Defuelling n°3 bis – flowrate profile with 6mm injection

Comments: this is a test is a repetition of n°3 with 6mm injector diameter, with faster flowrate ramp at the beginning, around 8 g/s for 700s followed by the rest at 1 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 407 bar, 9°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling strategy looks efficient, by strongly decreasing the pressure and almost reaching the tank limit temperature, then a slower flowrate brings back all temperatures in a more acceptable range. The influence of the injection diameter can't be identified here, it is probably negligible.

Following this test, the tank was completely defuelled, purged with nitrogen. After that the 4 times 3mm radial injector replaced the 6mm injector and the tank was prepared at 20 bar for the next test.

5.4.4.12 Fill FTD n°7+ Defuelling n°6 bis

Table 96: Fill FTD n°7 details

Date	9th October
Afternoon - Fill FTD n°7	17:00 - 19:00
Weather	North wind / Sun on the front upper part of the tank/ ~19°C ambient
Stabilization duration	All night

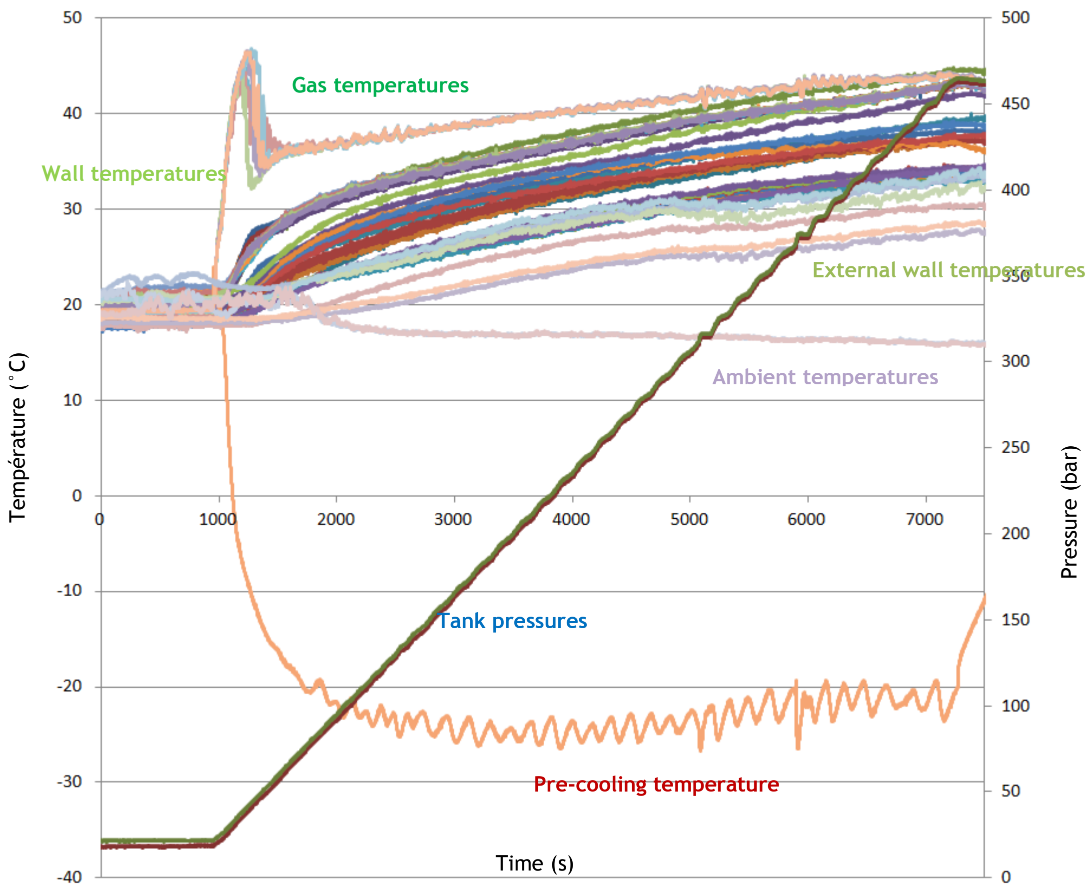


Figure 125: Fill FTD n°7 - radial injector slower flowrate

Comments: this test is performed at the low flowrate with a radial injector (4x3mm) injector, to compare it with the cases with the 3mm and the 6mm diameter injector. The fuelling ramp rate was around 0,1 bar/s and it stopped on a pressure condition. The pre-cooling reaches -23°C. Stratification can't be identified with these. The clear impact of the radial injection is difficult to identify at a first look.

Table 97: Defuelling n°6 bis details

Date	12th October
Morning - Defuelling n°6 bis	08:00 - 12:00
Weather	Strong south wind /no sun/ ~10°C ambient
Stabilization duration	4 h 50 min

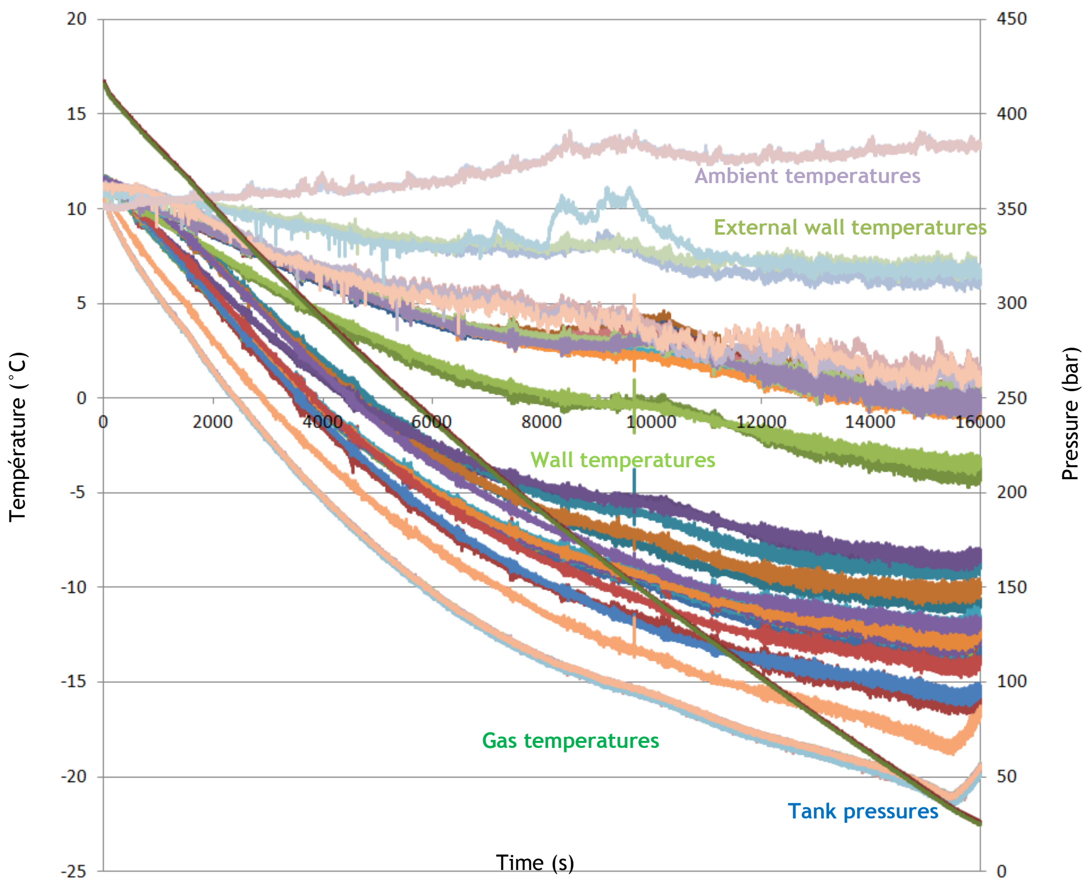


Figure 126: Defuelling n°6 bis - slow flow rate with radial injection

Comments: this is a test with slower flowrate ramp around 1 g/s The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 410 bar, 10°C. The recording was stopped when this difference was less than 3°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling reaches higher final temperatures as the defuelling time was longer. This test seems to reach lower temperatures than the 3mm injector similar test and similar to 6mm injector test, but no clear conclusions on the impact of the injector diameter comes out here.

5.4.4.1 Heterogeneities n°1 + Defuelling n°2 bis

Table 98: Heterogeneities n°1 details

Date	12th October
Afternoon – Heterogeneities n°1	16:50 – 17:25
Weather	Slight south wind/Rainy/ ~12°C ambient
Stabilization duration	All night

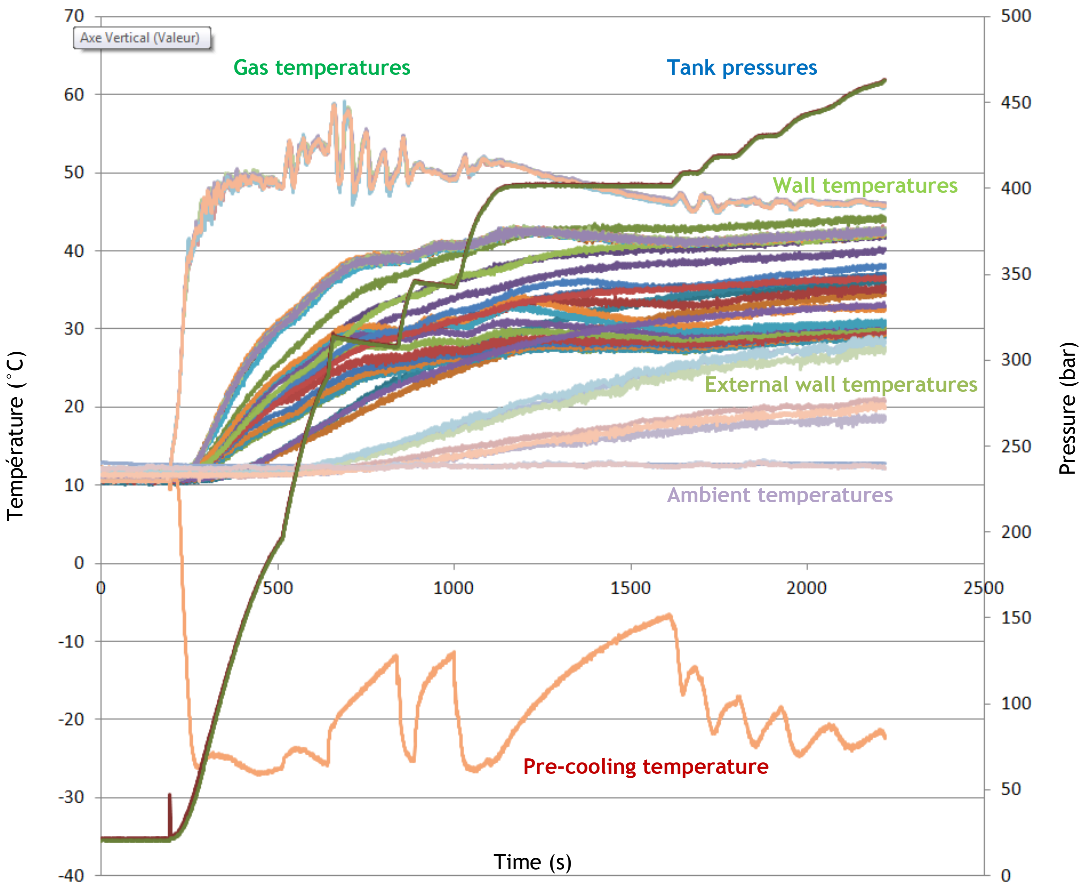


Figure 127: Heterogeneities n°1 - fast then slow fill

Comments: this test is performed to identify the energy profile impact on the final gas temperature. In this first test the fuelling begins with a high flowrate at 32 g/s (ramp rate 1 bar/s for 300s), followed by a slow flow rate at 2,8 g/s (0,1 bar/s for 1150s) and stopped on a pressure condition. The pre-cooling reaches -25°C. The regulation of the slow was inaccurate, creating a lot of fluctuations and stops in the second part of the fuelling. It will have to be compared to the second heterogeneities test. Max reached temperature 59°C and final temperature 46°C will have to be compared.

Table 99: Defuelling n°2 bis details

Date	13th October
Morning - Defuelling n°3 bis	08:30 – 10:30
Weather	No wind / Slight rain / ~12°C ambient
Stabilization duration	6h 20 min

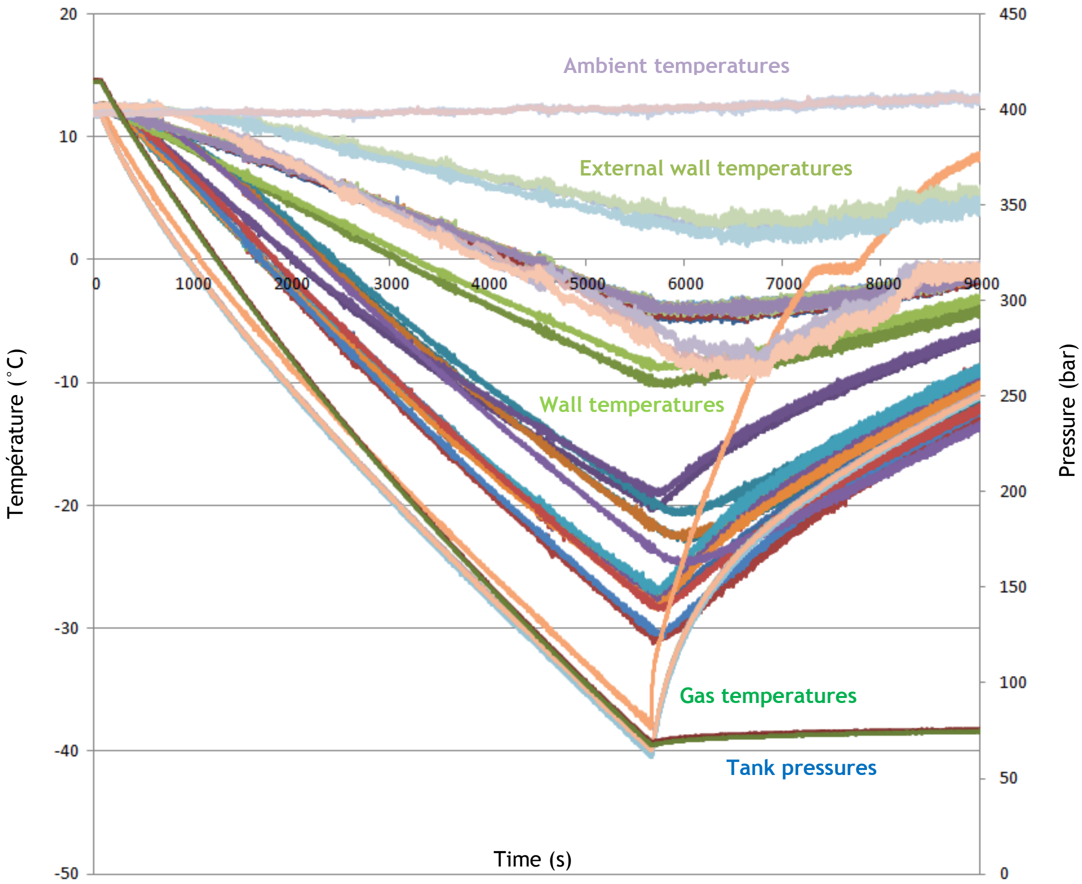


Figure 128: Defuelling n°2 bis – reference case with radial injection

Comments: this is a test is a repetition of n°2 with radial injector diameter, at a constant defuelling rate of 2 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 414 bar, 12°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed.

5.4.4.2 Heterogeneties n°2 + Defuelling n°3 bis

Table 100: Heterogeneities n°2 details

Date	13th October
Afternoon – Heterogeneities n°2	16:50 – 18:00
Weather	Strong north wind / Rainy/ ~12°C ambient
Stabilization duration	All night

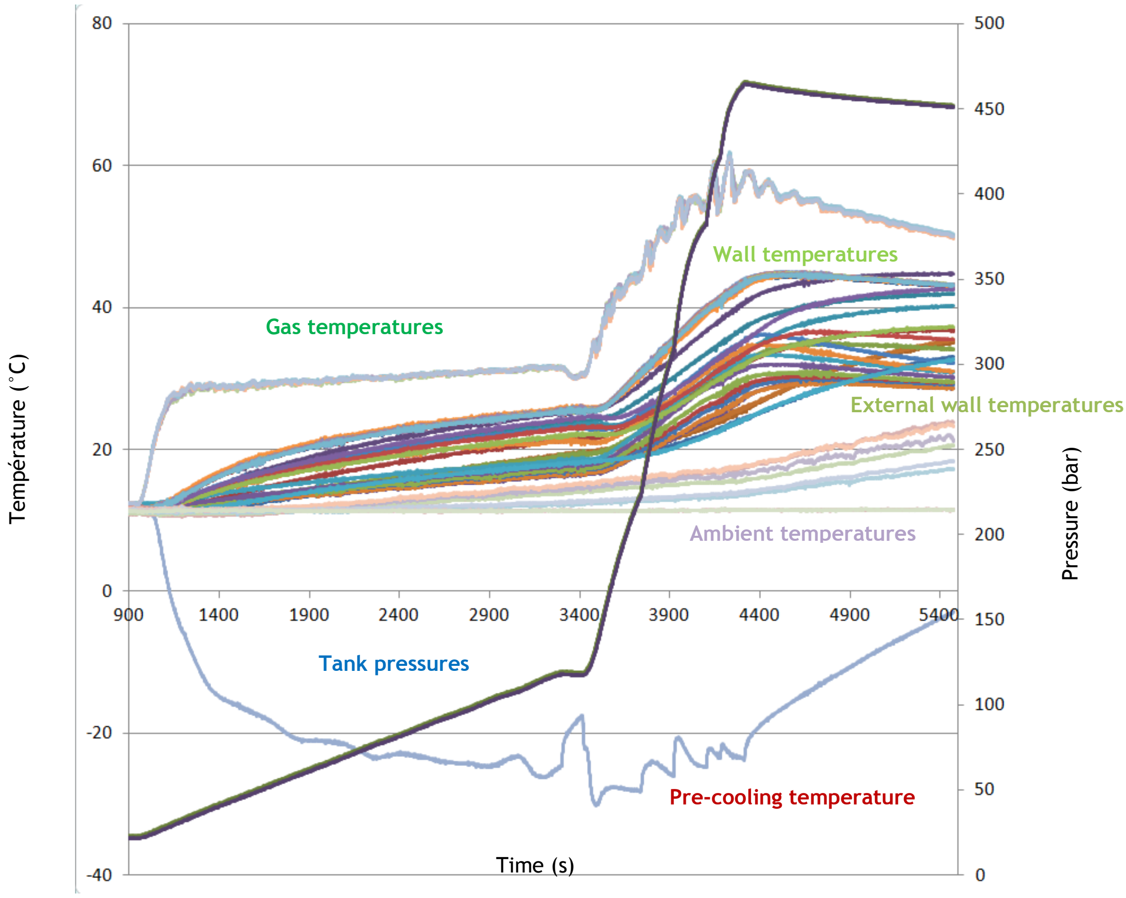


Figure 129: Heterogeneities n°2 - slow then fast fill

Comments: this test is performed to identify the energy profile impact on the final gas temperature. In this second test the fuelling begins with a slow flowrate at 2,8 g/s (ramp rate 0,08 bar/s for 1150s), followed by a fast flowrate at 32 g/s (1,2 bar/s for 300s) and stopped on a pressure condition. The pre-cooling reaches -26°C. Compared to the first heterogeneities test, maximum reached temperature 61°C and final temperature 61°C are the final values. The conclusion that the maximum reached temperature is independent from the fuelling profile, with the same amount of cold given to H2 seems good. This will have to be confirmed by simulation, but the maximum temperature reached between the liner and the composite also goes in this direction.

Table 101: Defuelling n°3 bis details

Date	14^{th} October
Morning - Defuelling n°3 bis	09:15 - 11:45
Weather	Morning cold/Strong north wind/ ~6°C ambient
Stabilization duration	5 h 00 min

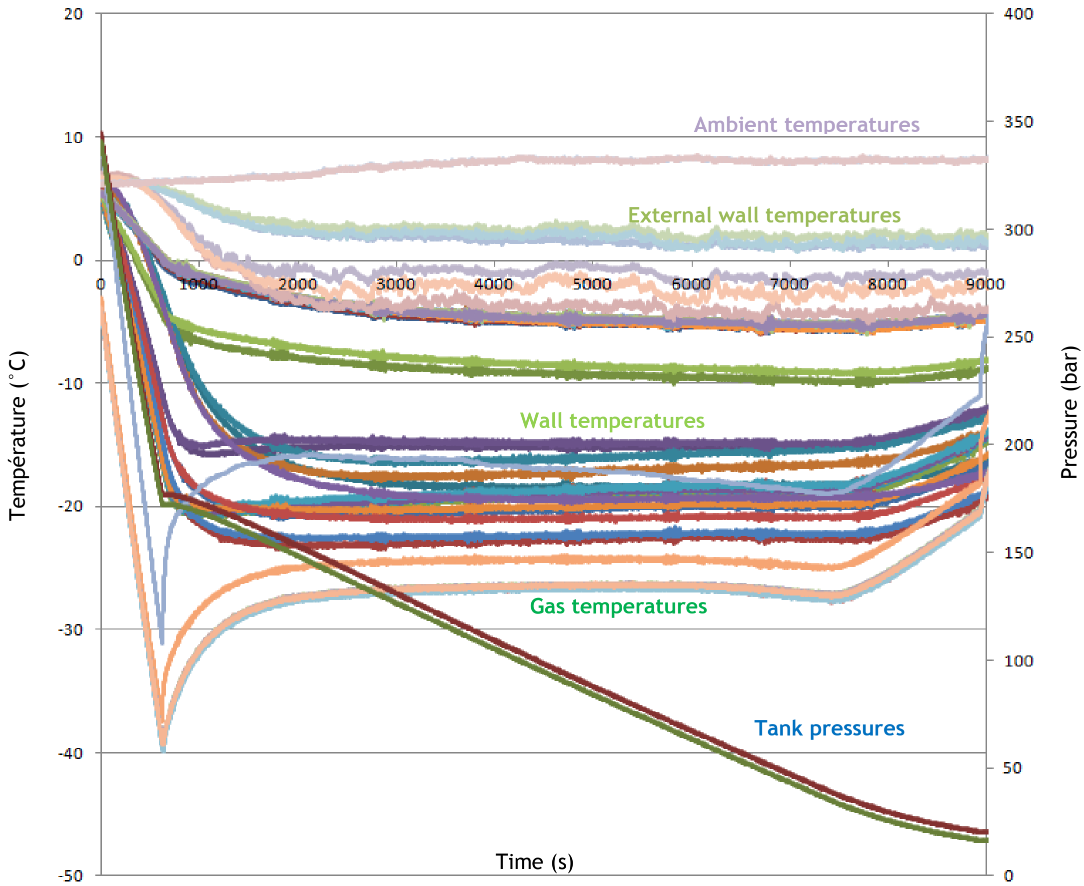


Figure 130: Defuelling n°3 bis - pressure profile with radial injection

Comments: this is a test is a repetition of n°3 with radial injector diameter, with faster flowrate ramp at the beginning, around 8 g/s for 700s followed by the rest at 1 g/s. The defuelling started with an ambient / gas average temperature difference of ~ 0°C at 391 bar, 6°C. We can also see here the temperature stratification. On some of the sensors some noise could be observed. This defuelling strategy looks efficient, by strongly decreasing the pressure and almost reaching the tank limit temperature, then a slower flowrate brings back all temperatures in a more acceptable range. The influence of the injection diameter can't be identified here, it is probably negligible. We reach similar temperatures with the different injectors.

Once the tests finished a complete defuelling was performed and the tank purged and packed once the instrumentation was removed. Similar phenomenon could be observed on the short and large tanks. However the large tank was too big to get a complete instrumentation. From a raw data analysis it is therefore easier to draw conclusions on the impact of parameters in the short tank

5.5 Test campaign on Type III short tank at ET

5.5.1 Objectives

Ludwig-Bölkow-Systemtechnik GmbH requested ET EnergieTechnologie (ET) to perform tests with hydrogen gas storage tanks to evaluate its temperature behavior during filling and emptying. An exact description of the test is described in the following chapters.

Applicable Documents

The test was performed on the basis of the following requirement specifications:

1. D3-2_SpecificationExperimentalFillingProgram-on-single-instrumented-tanks_Final.pdf
2. Need for new experiments 02-06-2015 - to redo List (5).xlsx
3. #703.1_Test-Setup_V03.pdf

5.5.2 Abstract of results

The test was successful finished as described in the test procedure.

5.5.3 Abstract of results

The test set-up was built up and into the test stand at ET. This test stand includes a sealed temperature chamber capable for temperatures from -40°C to +85°C. A high pressure heat exchanger for the gas is installed and can be set from -40°C to +85°C.

Tank: Prototype Cylinder

Serial Number: T1602

Model: 3M040C700G6N-DRSX

Volume: 40 L

Working Temperature Range: -40°C to +85°C

Service pressure: 70 MPa @ +15°C

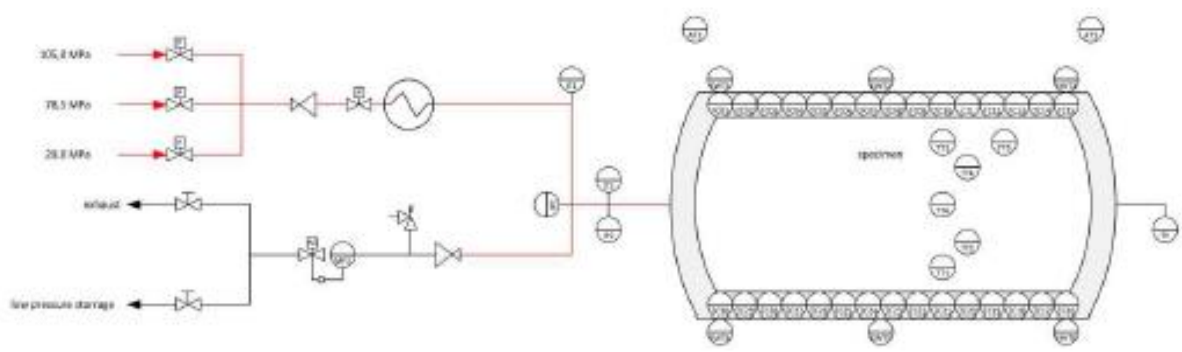


Figure 131: Flow chart of test set up (Rev.1 dated 30.08.2015)

Table 102: measurement point and device list

Pos.	Description	Type	Note	Value
IP1	Pressure transmitter	100 MPa G	Inlet pressure	[bar]
IP2	Pressure transmitter	100 MPa G	Inlet pressure	[bar]
TP	Pressure transmitter	100 MPa G	Tank pressure	[bar]
IT1	Internal gas temperature	Type K	Inlet temperature	[°C]
IT2	Internal gas temperature	Type K	Inlet temperature	[°C]
TT1	Internal gas temperature	Type K	n/a	[°C]
TT2	Internal gas temperature	Type K	n/a	[°C]
TT3	Internal gas temperature	Type K	n/a	[°C]
TT4	Internal gas temperature	Type K	n/a	[°C]
TT5	Internal gas temperature	Type K	n/a	[°C]
TT6	Internal gas temperature	Type K	n/a	[°C]
Pos.	Description	Type	Note	Value
EWT1	External Wall Temperature	Type K	n/a	[°C]
EWT2	External Wall Temperature	Type K	n/a	[°C]
EWT3	External Wall Temperature	Type K	n/a	[°C]
EWT4	External Wall Temperature	Type K	n/a	[°C]
EWT5	External Wall Temperature	Type K	n/a	[°C]
EWT6	External Wall Temperature	Type K	n/a	[°C]
AT1	Ambient Temperature	Type K	n/a	[°C]
AT2	Ambient Temperature	Type K	n/a	[°C]
TC1	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC2	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC3	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC4	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC5	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC6	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC7	Composite-Liner temperature	Type T	n/a	[°C]
TC8	Composite-Liner temperature	Type T	n/a	[°C]
TC9	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC10	Composite-Liner temperature	Type T	n/a	[°C]
TC11	Composite-Liner temperature	Type T	n/a	[°C]
TC12	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC13	Composite-Liner temperature	Type T	n/a	[°C]
TC14	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC15	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC16	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC17	Composite-Liner temperature	Type T	n/a	[°C]
TC18	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC19	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC20	Composite-Liner temperature	Type T	n/a	[°C]
TC21	Composite-Liner temperature	Type T	n/a	[°C]
TC22	Composite-Liner temperature	Type T	n/a	[°C]
TC23	Composite-Liner temperature	Type T	n/a	[°C]
TC24	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC25	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC26	Composite-Liner temperature	Type T	n/a	[°C]
TC27	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC28	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC29	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]
TC30	Composite-Liner temperature	Type T	Not working. Not in the Data sheet	[°C]

To avoid an oxygen-hydrogen mixture, the specimen was purged several times with nitrogen and followed with hydrogen. These steps guarantee a complete hydrogen atmosphere in the specimen.

Prior to the first test the measurement points have been calibrated with the following calibration devices.

Table 103: calibration device list

Device	Serial No.	Usage	Note
Pressure sensor 0-100 MPa	4403069	100 MPa sensor	n.a.

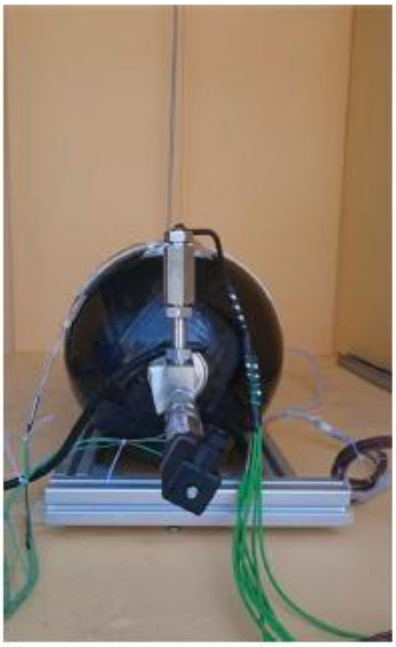


Figure 132: Tank with Pressure sensor TP

Figure 133: IT2 and IP2 (22cm from the inlet of the tank)

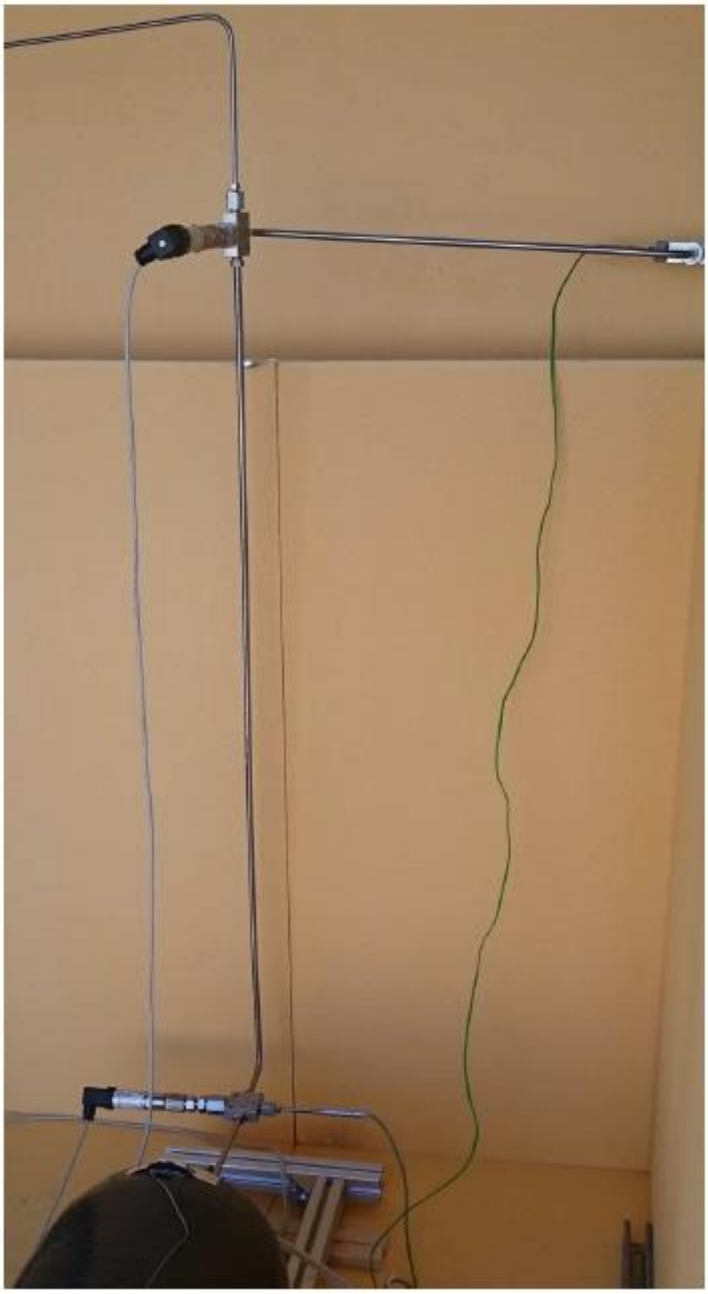


Figure 134: IP1 155cm from the inlet of the tank; IT1 210cm from the inlet of the tank

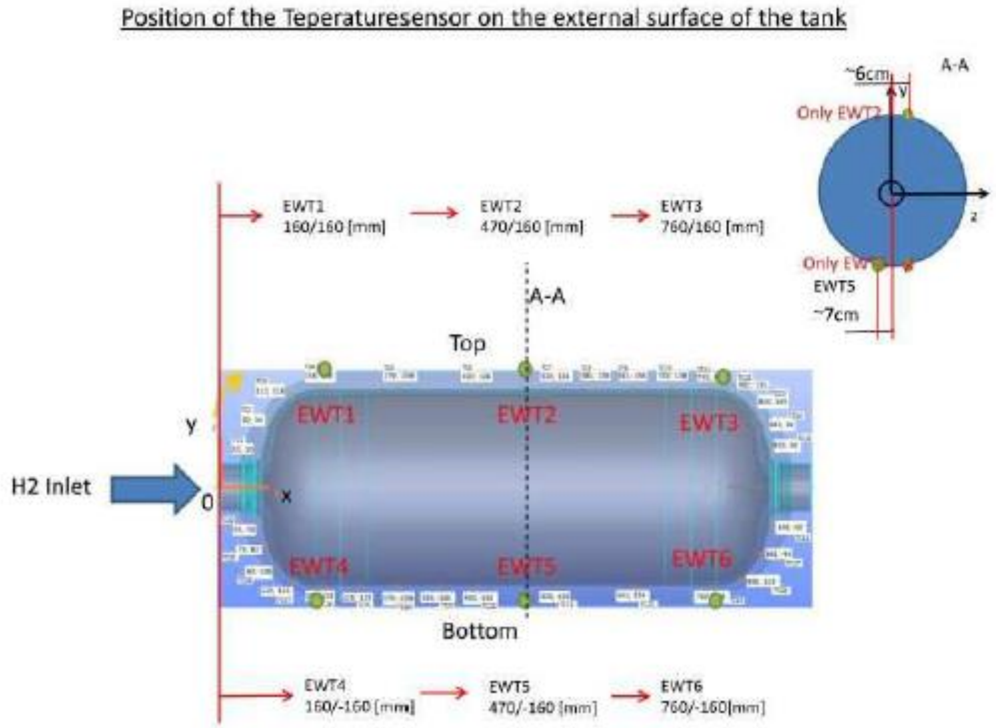


Figure 135: Position Thermocouple surface V2

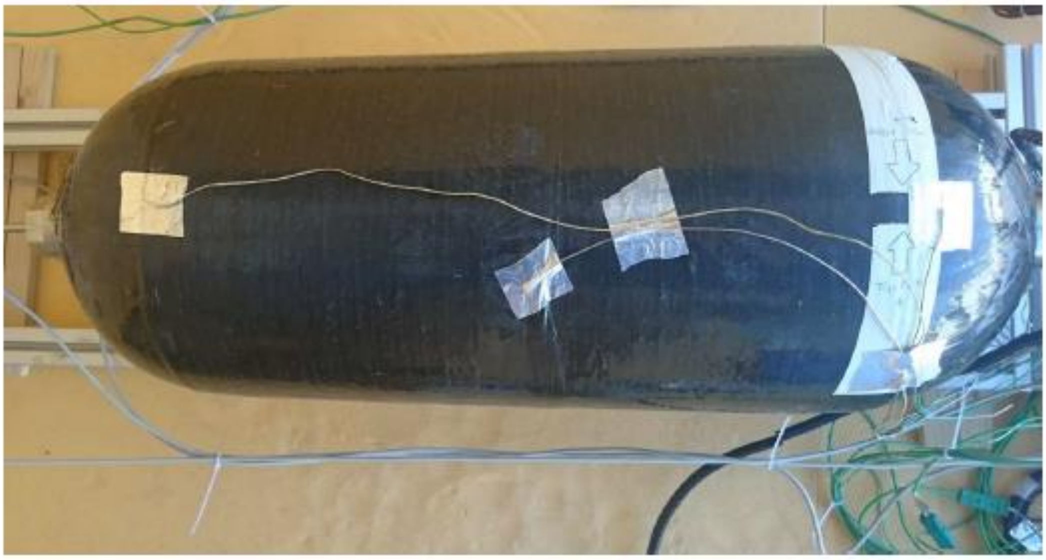


Figure 136: Thermocouple on the upper side of the tank V2

Figure 137: thermocouple on the lower side of the tank (tank not shown in test position; rotated 90° to show position of thermocouple) V2

5.5.3.1 Documentation of customer parts

Table 104: documentation of specimen usage

Specimen No.	Test Pos.	Installation date	Uninstallation date
T1602	1	28.08.2015	01.10.2014

5.5.4 Test procedure

5.5.4.1 Test preparation

Following a timely description shows which steps were performed during the test preparation. For all steps described measurement data and graphs are available.

Date/Time	Description
28.08.2015	
10:00	Installation specimen in to the test stand
03.09.2015	
12:00	Purging with N2, 6x 5,5-0 bar
13:35	Conditioning with H2, 4x 20-0 bar
15:00	Leak and pressure test. Specimen was pressurized stepwise up to 800 bar and checked for leaks with a hydrogen handheld sensor. No leaks were detected during the test.
15:00	Calibration pressure sensor

5.5.4.2 Main test 04.09.2015 to 22.09.2015

Following a timely description of the test shows which steps were performed during the test. For all steps described measurement data and graphs are available.

Date/Time	Description
04.09.2015	
13:30	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-SMV--exp1* - D1 = 3mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 8 [g/s]
18:10	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling--exp1* - Ambient temp. 20°C - Average mass flow 0,376 [g/s] - <20 [bar] or Tgas -40 [°C]
09.09:2015	
08:20	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling—exp3* - Ambient temp. 20°C - Average mass flow 0,5 [g/s] - <20 [bar] or Tgas -40 [°C]

Date/Time	Description
09.09:2015	
20:00	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling—exp5* - Ambient temp. 20°C - Average mass flow 0,125 [g/s] - <20 [bar] or Tgas -40 [°C]
10.09:2015	
15:30	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling--exp6* - Ambient temp. 20°C - 1,5 [g/s] for 500s, then 0,2 [g/s] for the rest of the defueling - <20 [bar] or Tgas -40 [°C]
11.09:2015	
20:15	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling--exp7* - Ambient temp. 20 [°C] - 0,2 [g/s] for 3100s, then 1,5 [g/s] for the rest of the defueling - <20 [bar] or Tgas -40 [°C]
15.09.2015	
10:45	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-SMV—exp5* - D1 = 3mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 2 [g/s]
16:30	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling—exp9* - Ambient temp. 20°C - Average mass flow 0,188 [g/s] - <5 [bar] or Tgas -40 [°C]
16.09.2015	
08:00	Depressurize the specimen to atmospheric pressure - Purging with N2, 6x 5,5-0 bar - Changing the injector from 3mm to 6mm - Purging with N2, 6x 5,5-0 bar - Conditioning with H2, 4x 20-0 bar - Set ambient temperature to 20 [°C]
14:15	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-FTD--exp3*

Date/Time	Description
	- D1 = 6mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 8 [g/s]
17.09.2015	
13:30	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-FTD--exp4* - D1 = 6mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 2 [g/s]
18.09.2015	
08:00	Depressurize the specimen to atmospheric pressure - Purging with N2, 6x 5,5-0 bar - Changing the injector from 6mm to 10mm - Purging with N2, 6x 5,5-0 bar - Conditioning with H2, 4x 20-0 bar - Set ambient temperature to 20 [°C]
11:00	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-FTD--exp5* - D1 = 10mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 8 [g/s]
21.09.2015	
09:00	Start Test after initial cylinder and gas initial temperature equal to ambient temperature. Test: *Fill-FTD--exp6* - D1 = 10mm - Initial pressure: 20 [bar] - Ambient temp. 20 [°C] - Gas inlet temp. -20 [°C] - Average mass flow: 2 [g/s]
15:00	Depressurize the specimen to atmospheric pressure - Purging with N2, 6x 5,5-0 bar - Changing the injector from 10mm to 3mm - Purging with N2, 6x 5,5-0 bar - Conditioning with H2, 4x 20-0 bar - Set ambient temperature to -20 [°C]
22.09.2015	
08:00	Start Defueling after initial cylinder and gas initial temperature equal to ambient temperature. Defueling: *Defueling—exp8* - Ambient temp. -20°C - Average mass flow 0,125 [g/s] - <20 [bar] or Tgas -40 [°C]

5.5.5 Test finishing

Following a timely description of the test shows which steps were performed during the test.

30.09.2015	
10:00	Depressurize the specimen to atmospheric pressure - Purging with N2, 6x 5,5-0 bar
14:00	Dismount specimen from the test stand.

5.5.6 Test results and observations

All tests were successful finished as described in the test procedure.

The Calculation of SOC value results from the average temperature of the internal gas temperature (TT1 to TT6) and the pressure sensor TP. The calculation of the mass "M" results from the SOC value.

5.5.7 Appendix I

Document title:
20150903_150835_#703.1_test_preperation

Document typ:
pdf

Number of pages:
2

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Test preperation

EnergieTechnologie
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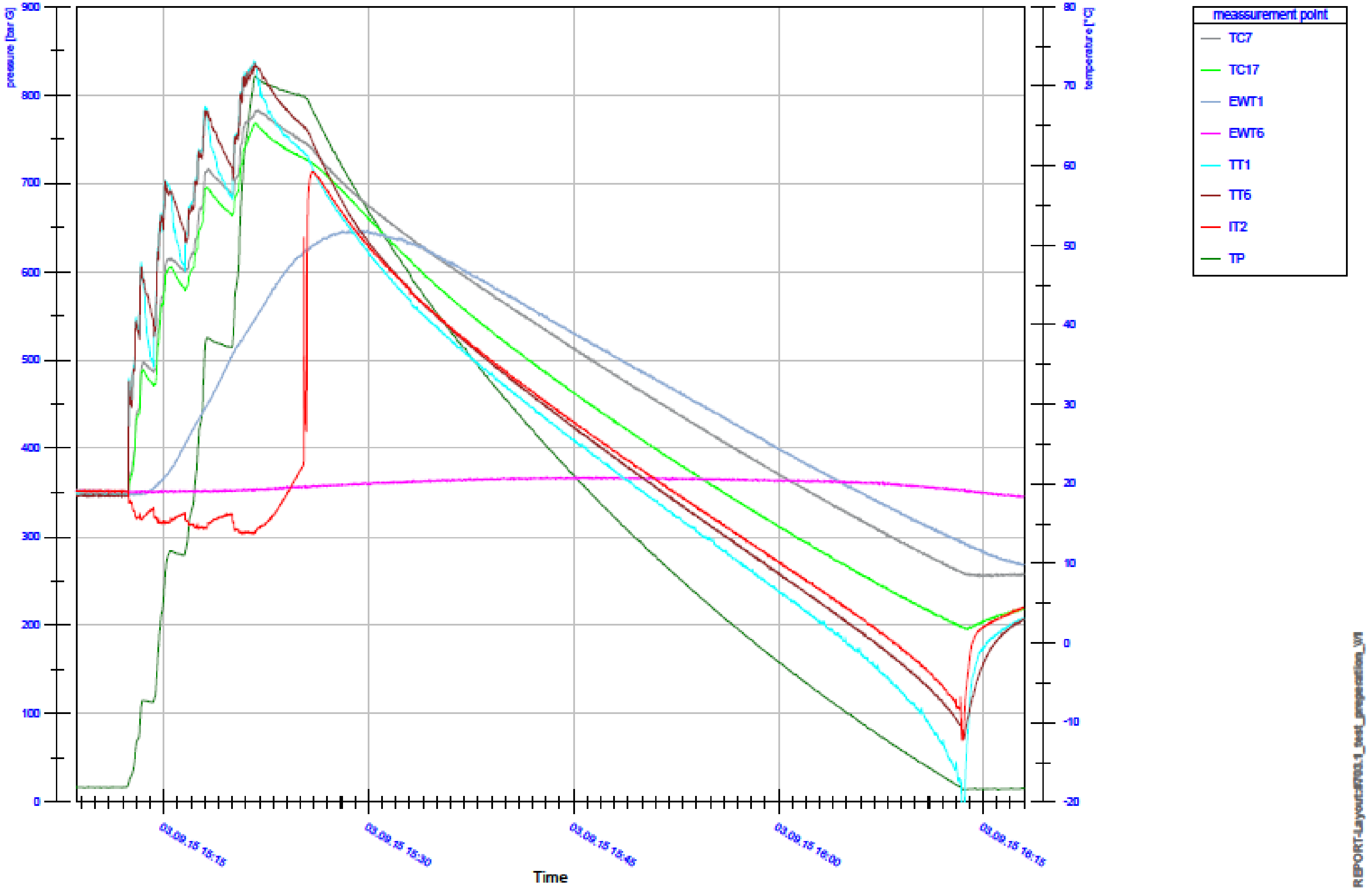
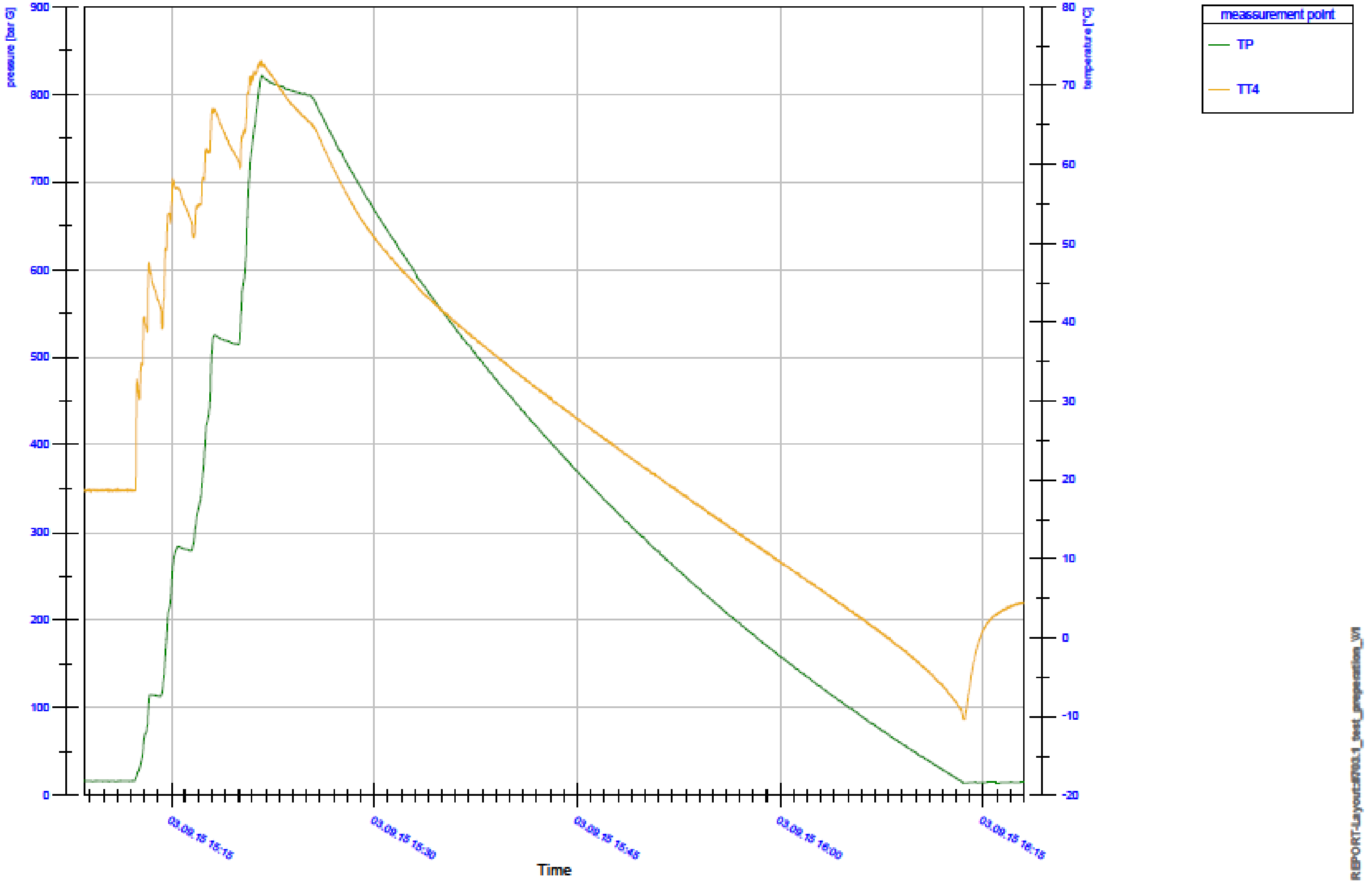


Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Test preperation



5.5.8 Appendix II

Document title:
#703.1_Filling Diagrams

Document typ:
pdf

Number of pages:
12

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-SMV--exp1

EnergieTechnologie
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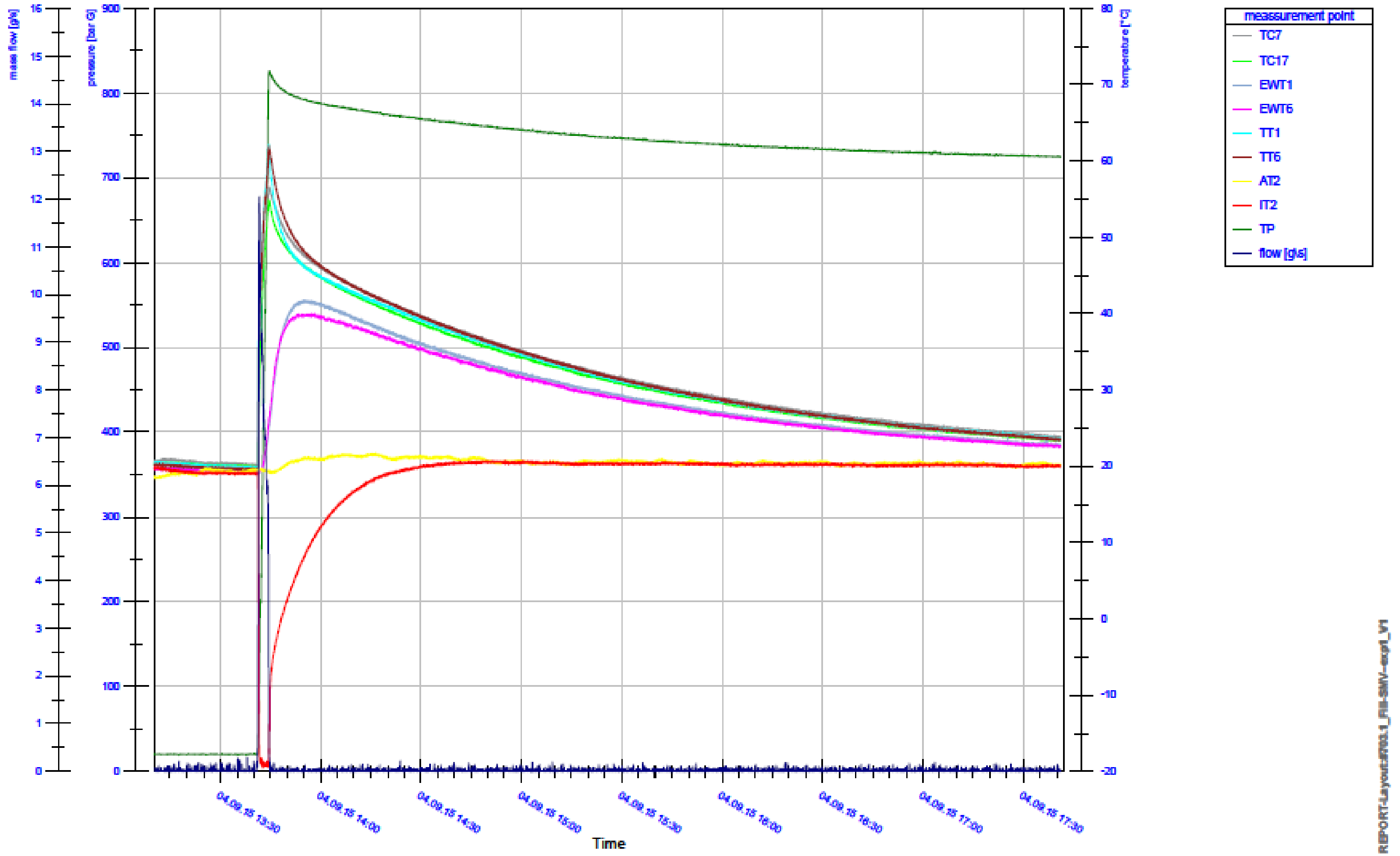

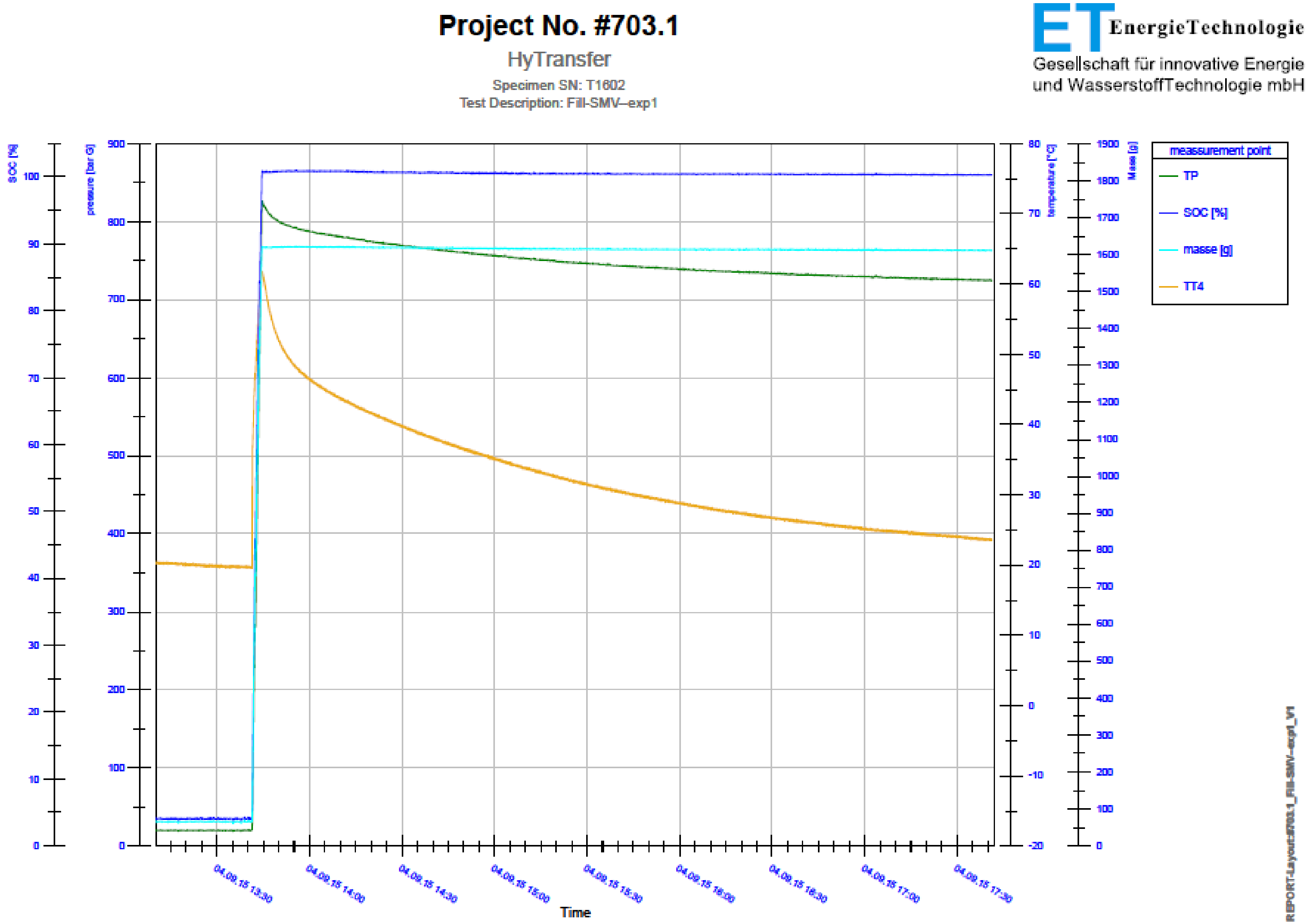

Project No. #703.1
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Test Description: Fill-SMV--exp1
EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH
measurement point
TP
SOC [%]
masse [g]
TT4
SOC [%]
pressure [bar G]
temperature [°C]
Masse [g]
Time

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-SMV--exp5

EnergieTechnologie
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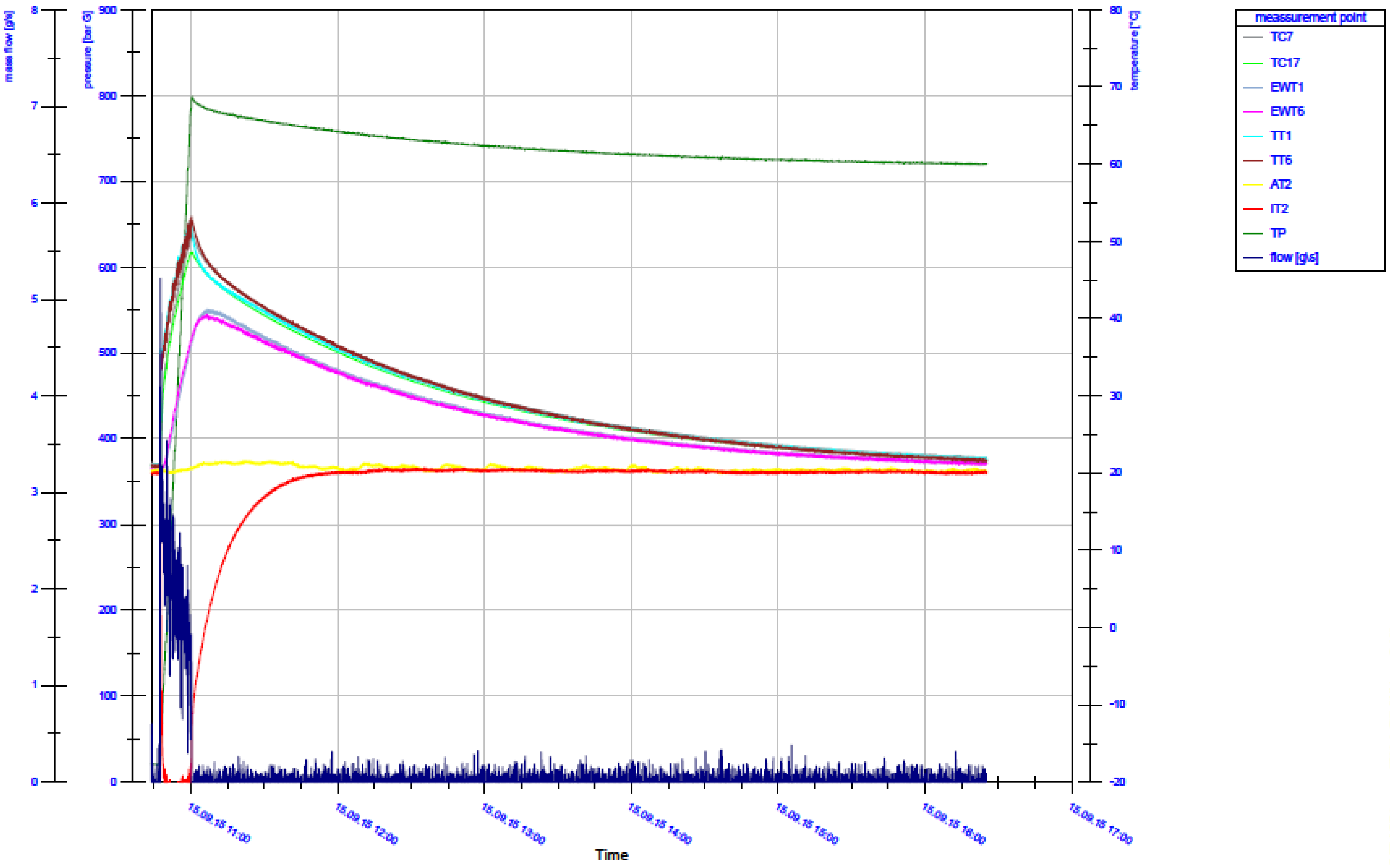

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-SMV--exp5

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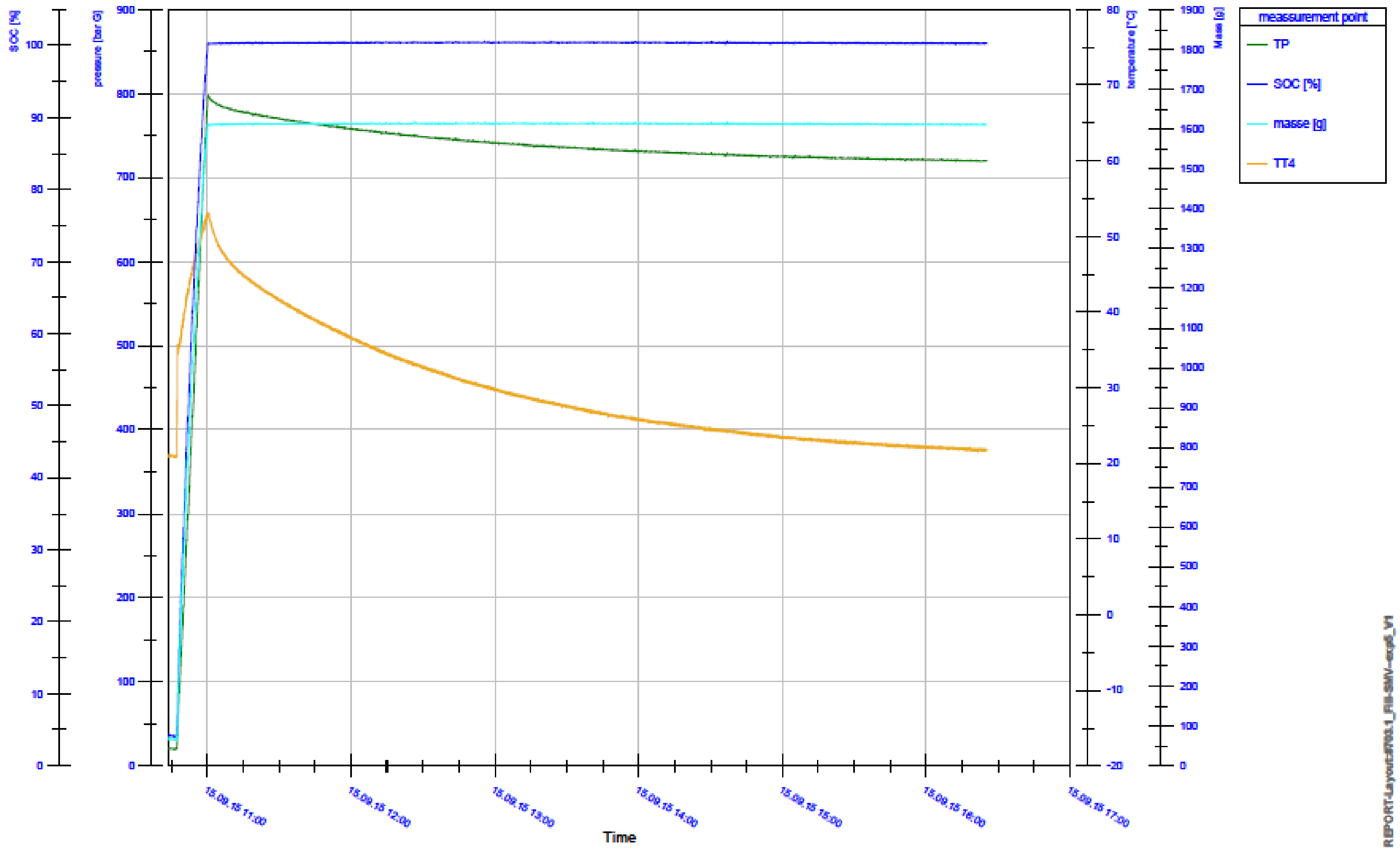

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-FTD--exp3

EnergieTechnologie
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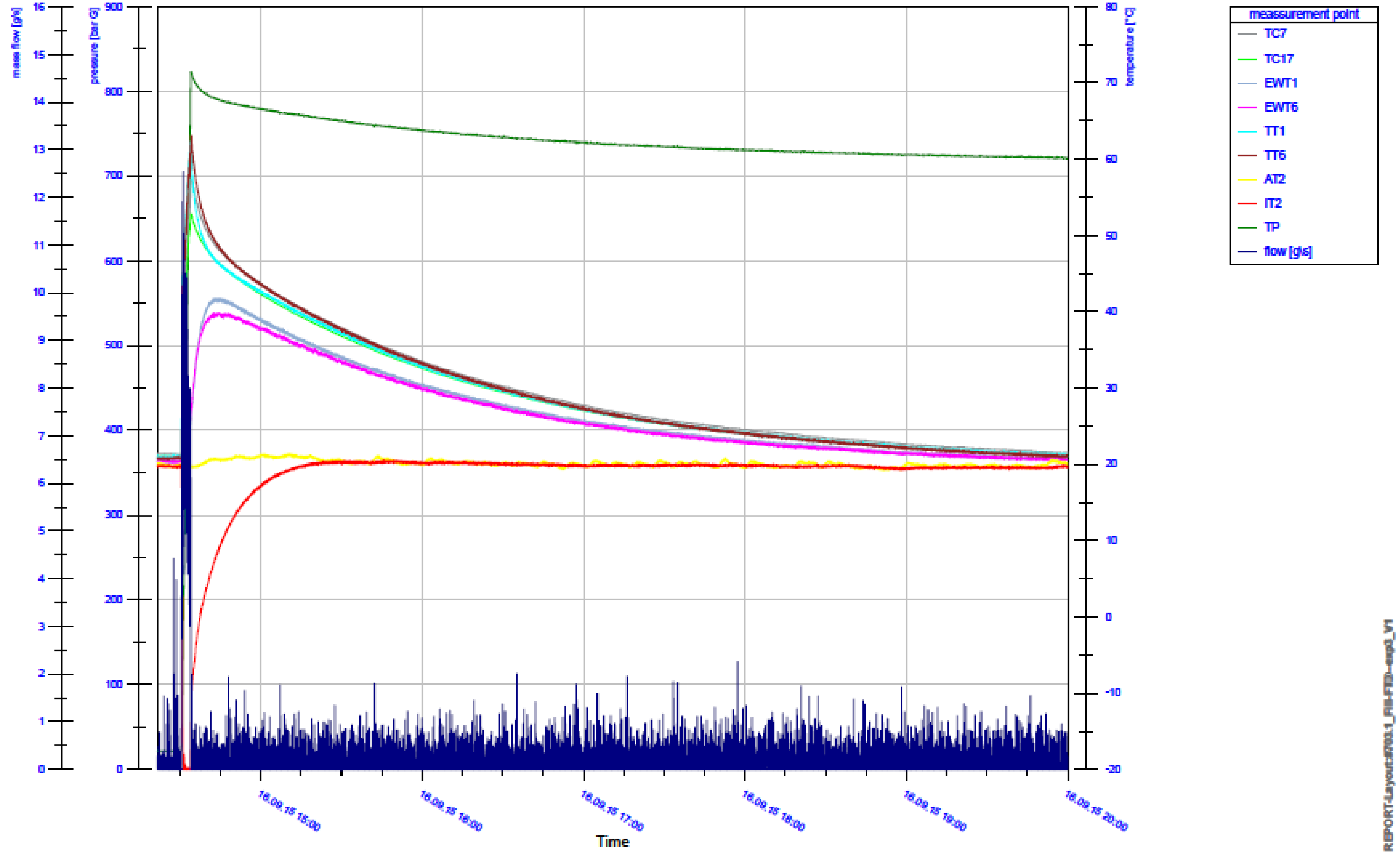

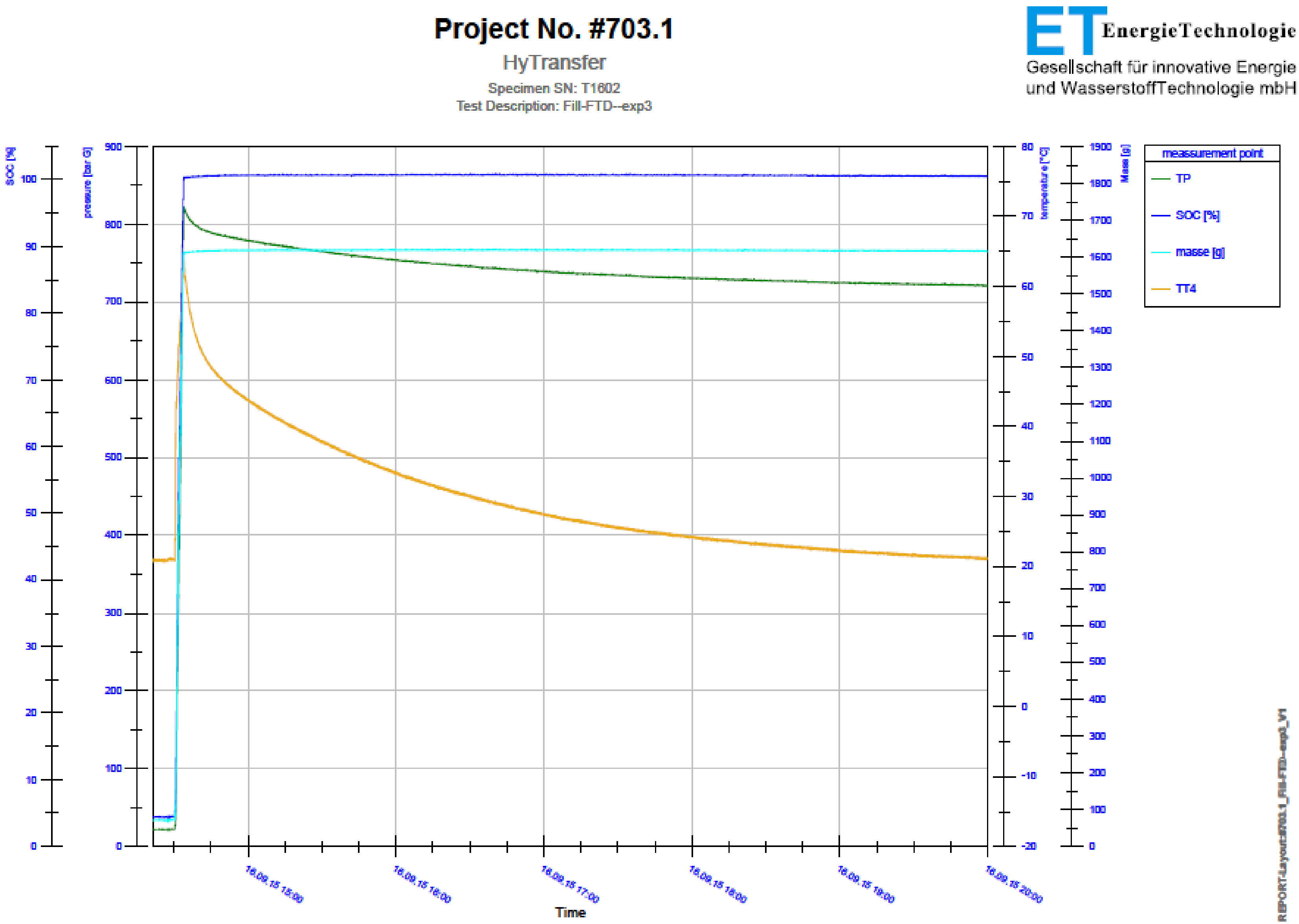
Project No. #703.1
HyTransfer
Specimen SN: T1602
Test Description: Fill-FTD--exp3
EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH
SOC [%]
pressure [bar G]
temperature [°C]
Masse [g]
measurement point
TP
SOC [%]
masse [g]
TT4
Time
16.09.15 15:00
16.09.15 16:00
16.09.15 17:00
16.09.15 18:00
16.09.15 19:00
16.09.15 20:00
REPORT-Layout-#703.1_Fill-FTD--exp3_V1

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-FTD--exp4

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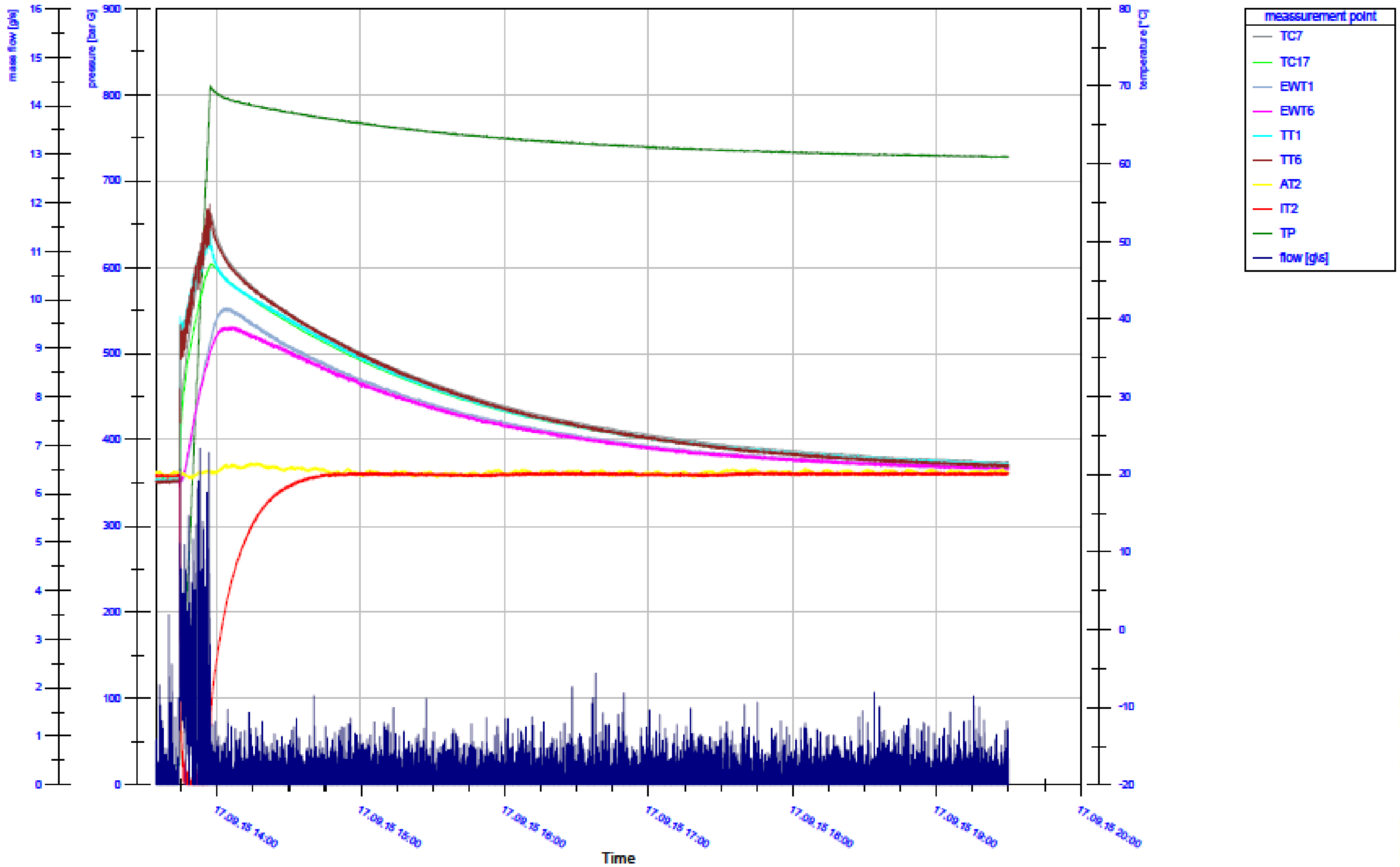

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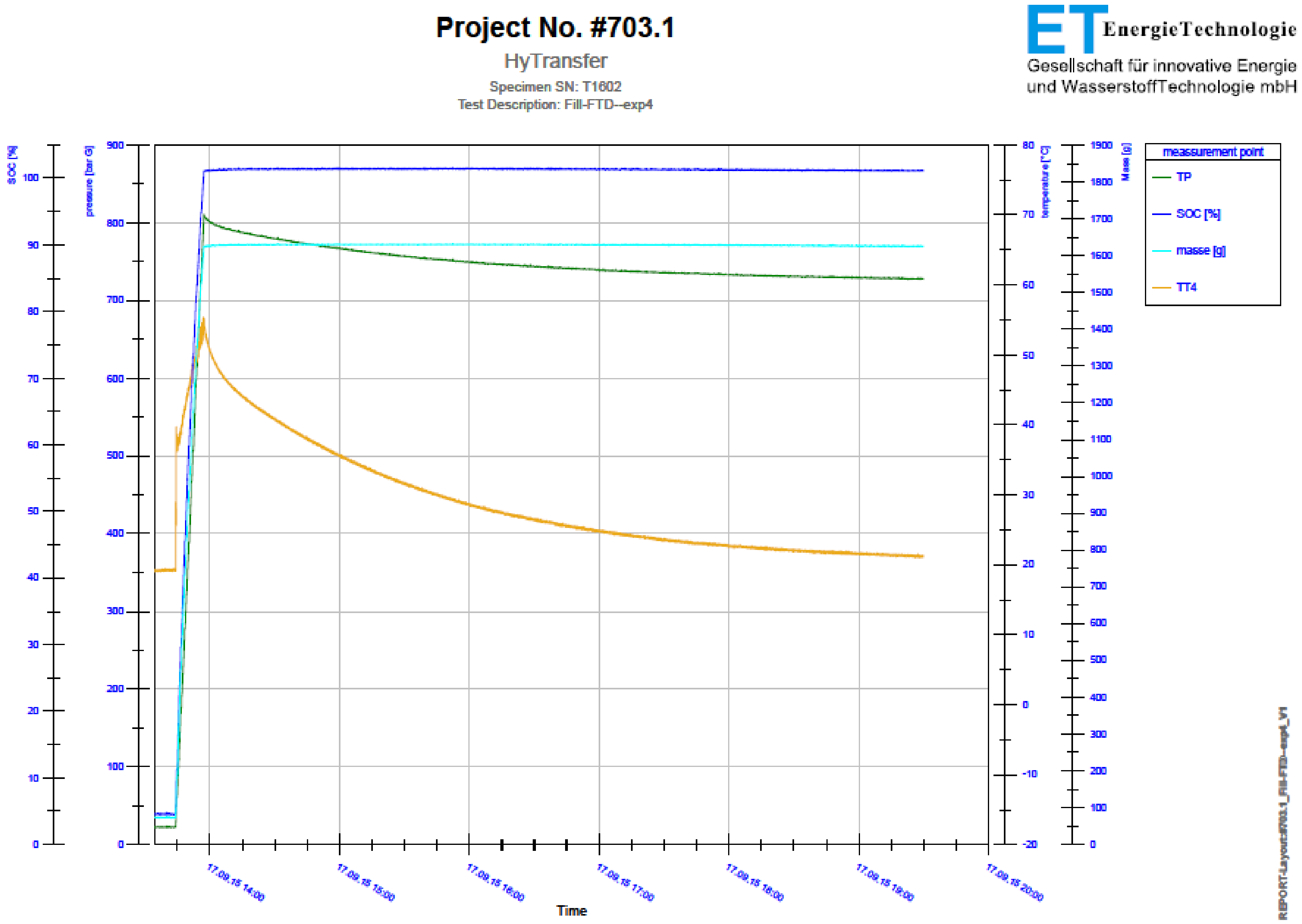

Project No. #703.1
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EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH
SOC [%]
pressure [bar G]
temperature [°C]
Masse [g]
measurement point
TP
SOC [%]
masse [g]
TT4
17.09.15 14:00
17.09.15 15:00
17.09.15 16:00
17.09.15 17:00
17.09.15 18:00
17.09.15 19:00
17.09.15 20:00
Time

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-FTD--exp5

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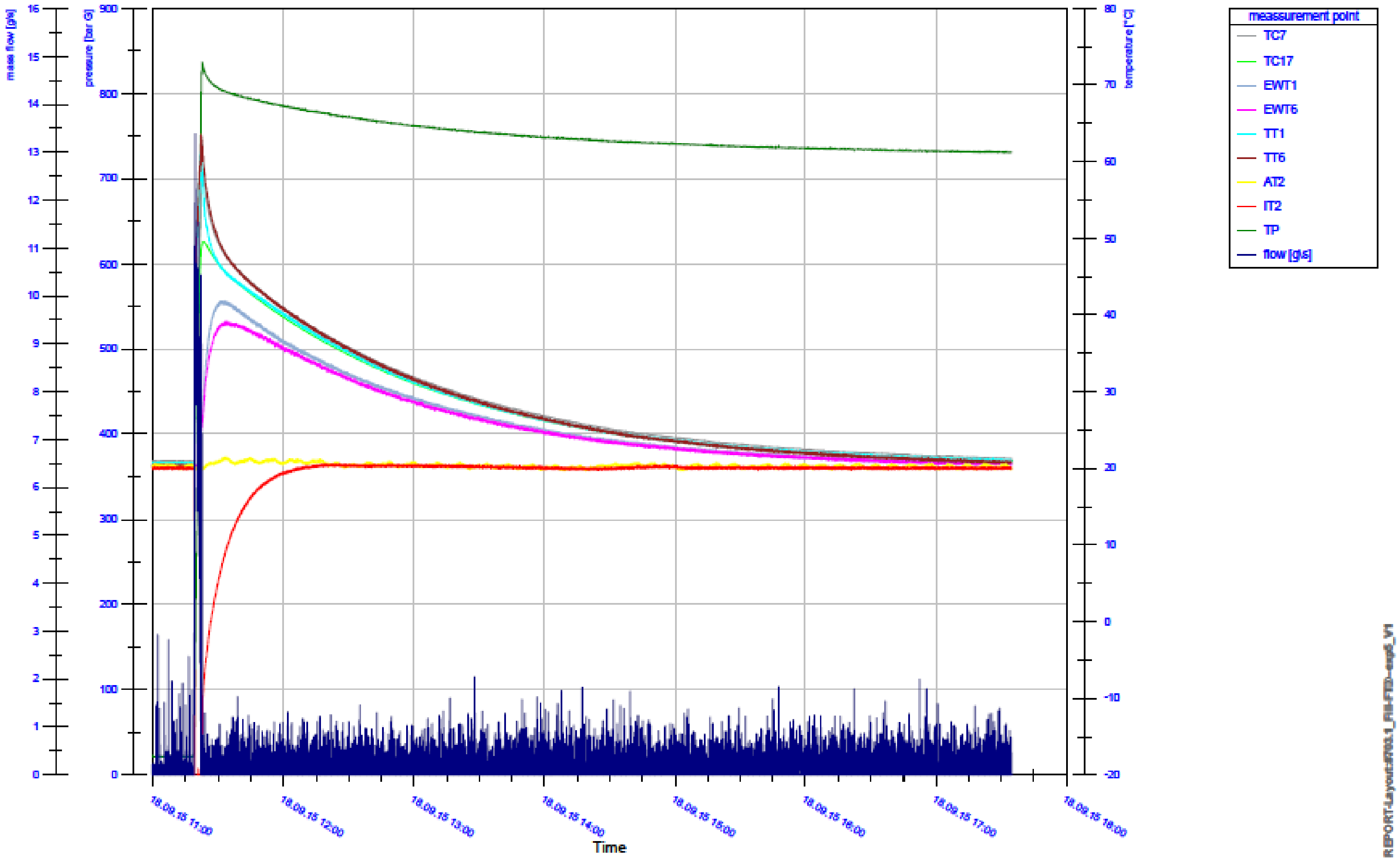

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-FTD--exp5

ET EnergieTechnologie
Gesellschaft für innovative Energie
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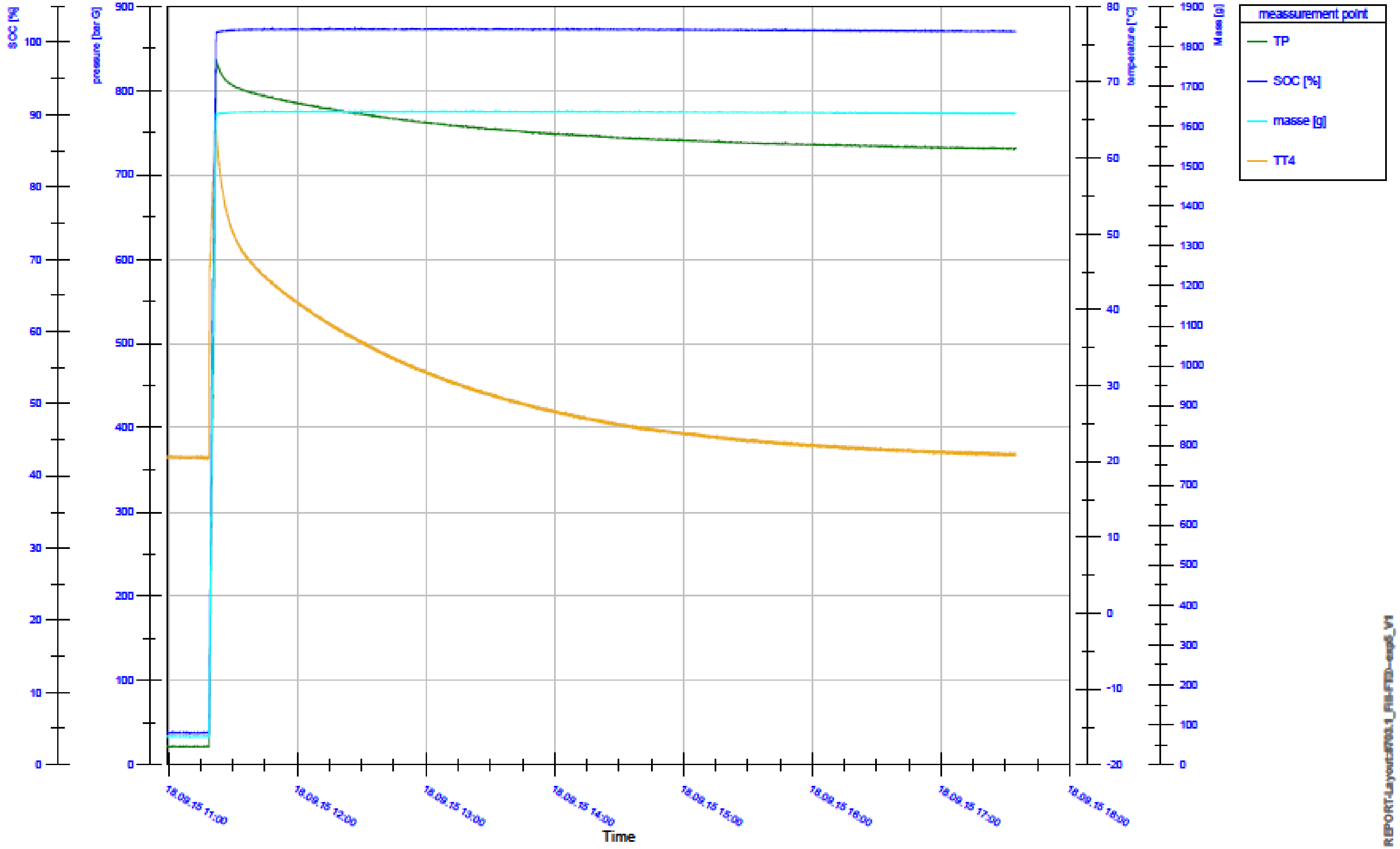


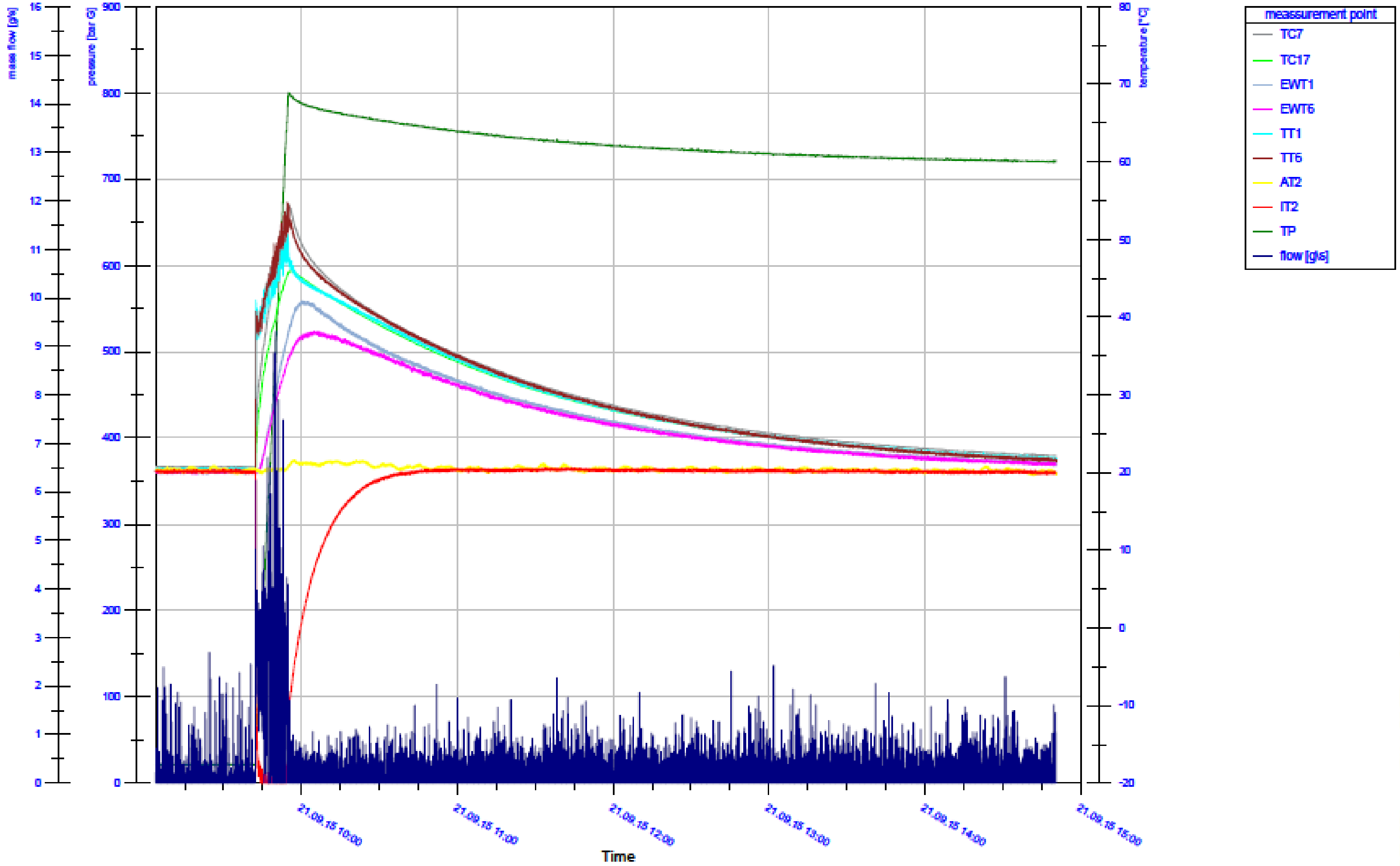
Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: Fill-FTD--exp6

ET EnergieTechnologie
Gesellschaft für innovative Energie
und WasserstoffTechnologie mbH



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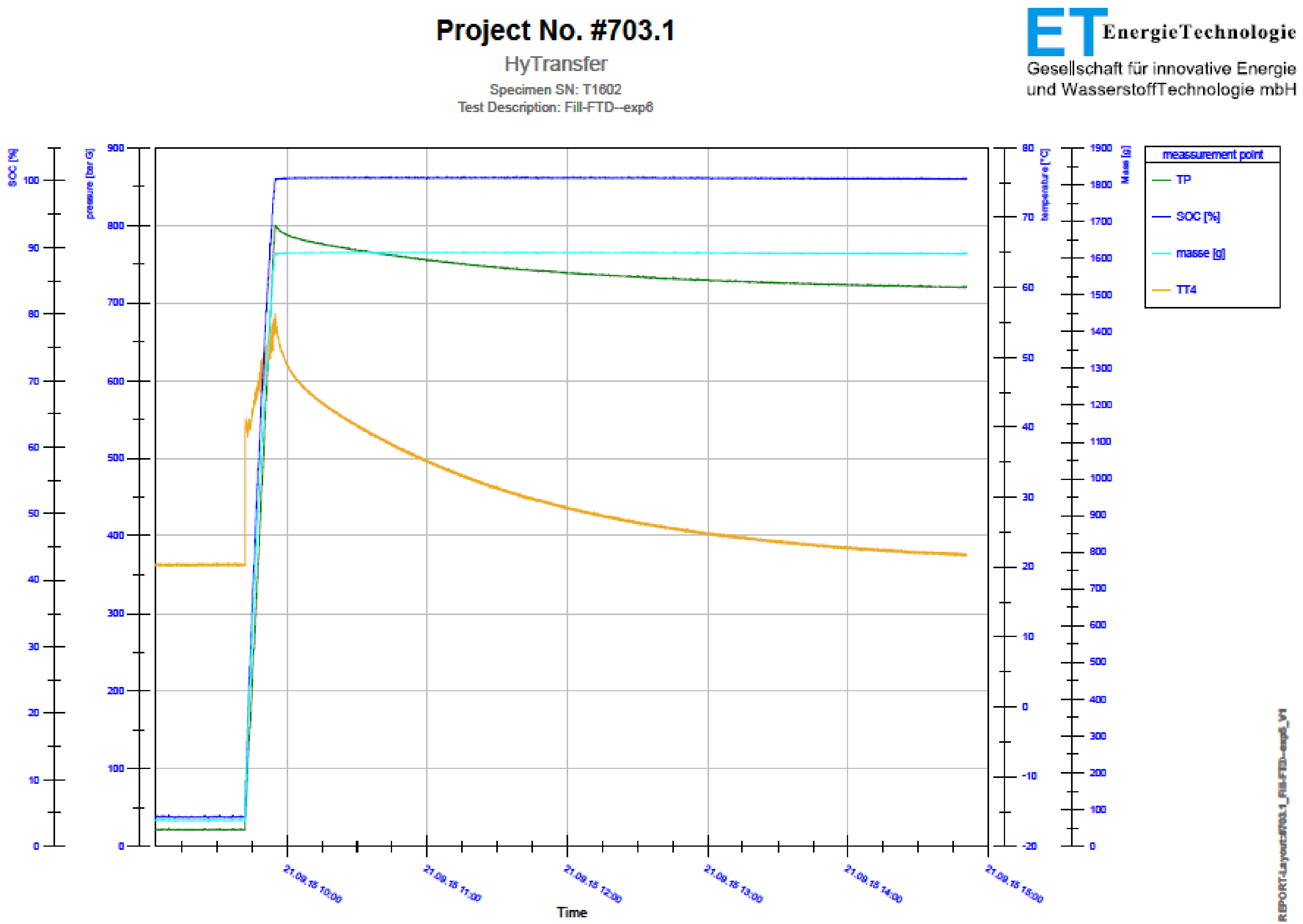
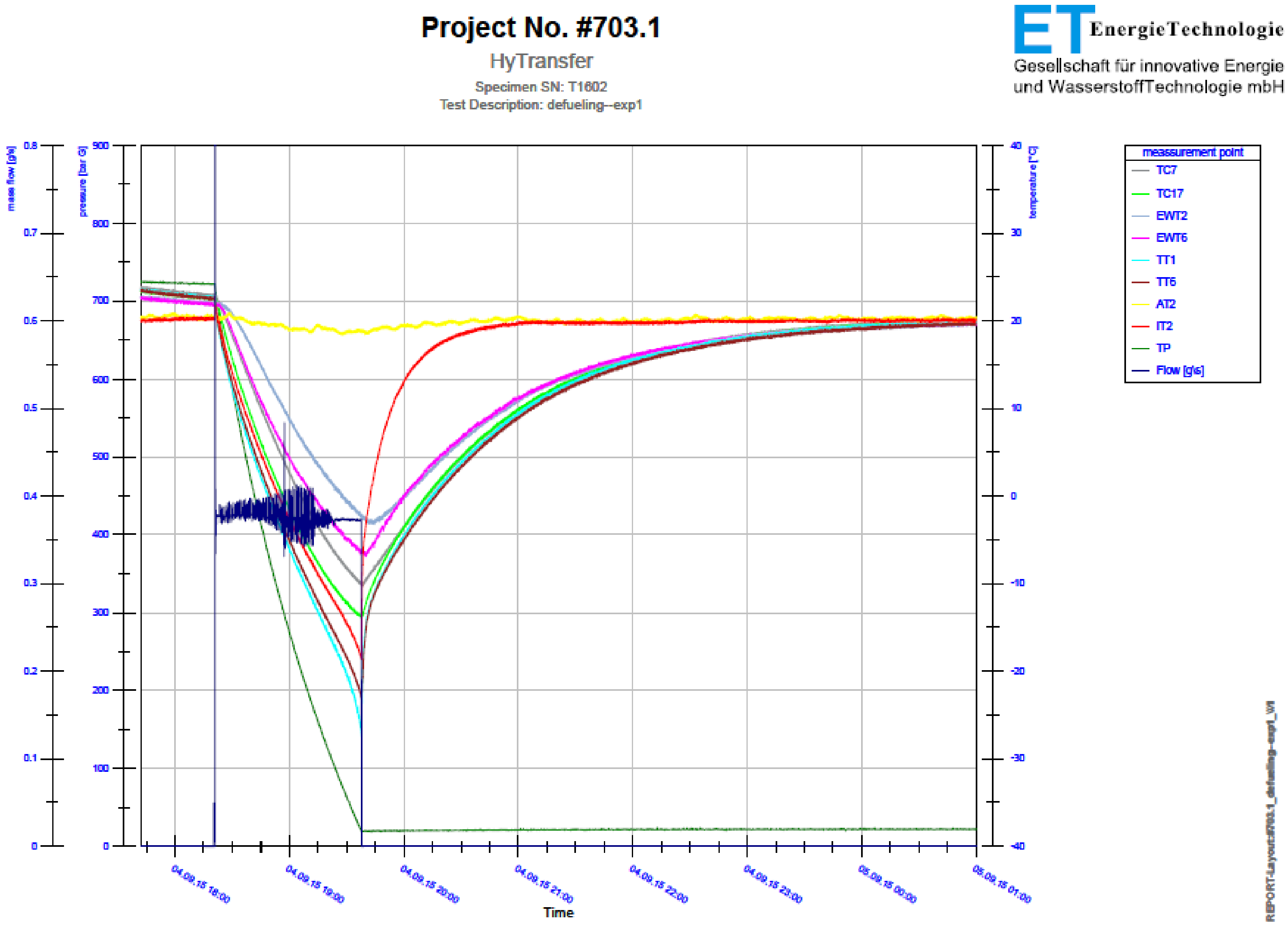

Project No. #703.1
HyTransfer
Specimen SN: T1602
Test Description: Fill-FTD--exp6
EnergieTechnologie
Gesellschaft für innovative Energie
und WasserstoffTechnologie mbH
SOC [%]
pressure [bar G]
temperature [°C]
Mass [g]
measurement point
TP
SOC [%]
masse [g]
TT4
21.09.15 10:00
21.09.15 11:00
21.09.15 12:00
21.09.15 13:00
21.09.15 14:00
21.09.15 15:00
Time

5.5.9 Appendix III

Document title:
#703.1_Defueling Diagrams

Document typ:
pdf

Number of pages:
14



Project No. #703.1
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Test Description: defueling--exp1
EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH
mass flow [g/s]
pressure [bar G]
temperature [°C]
Time
measurement point
TC7
TC17
EWT2
EWT6
TT1
TT6
AT2
IT2
TP
Flow [g/s]
04.09.15 18:00
04.09.15 19:00
04.09.15 20:00
04.09.15 21:00
04.09.15 22:00
04.09.15 23:00
05.09.15 00:00
05.09.15 01:00

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp1

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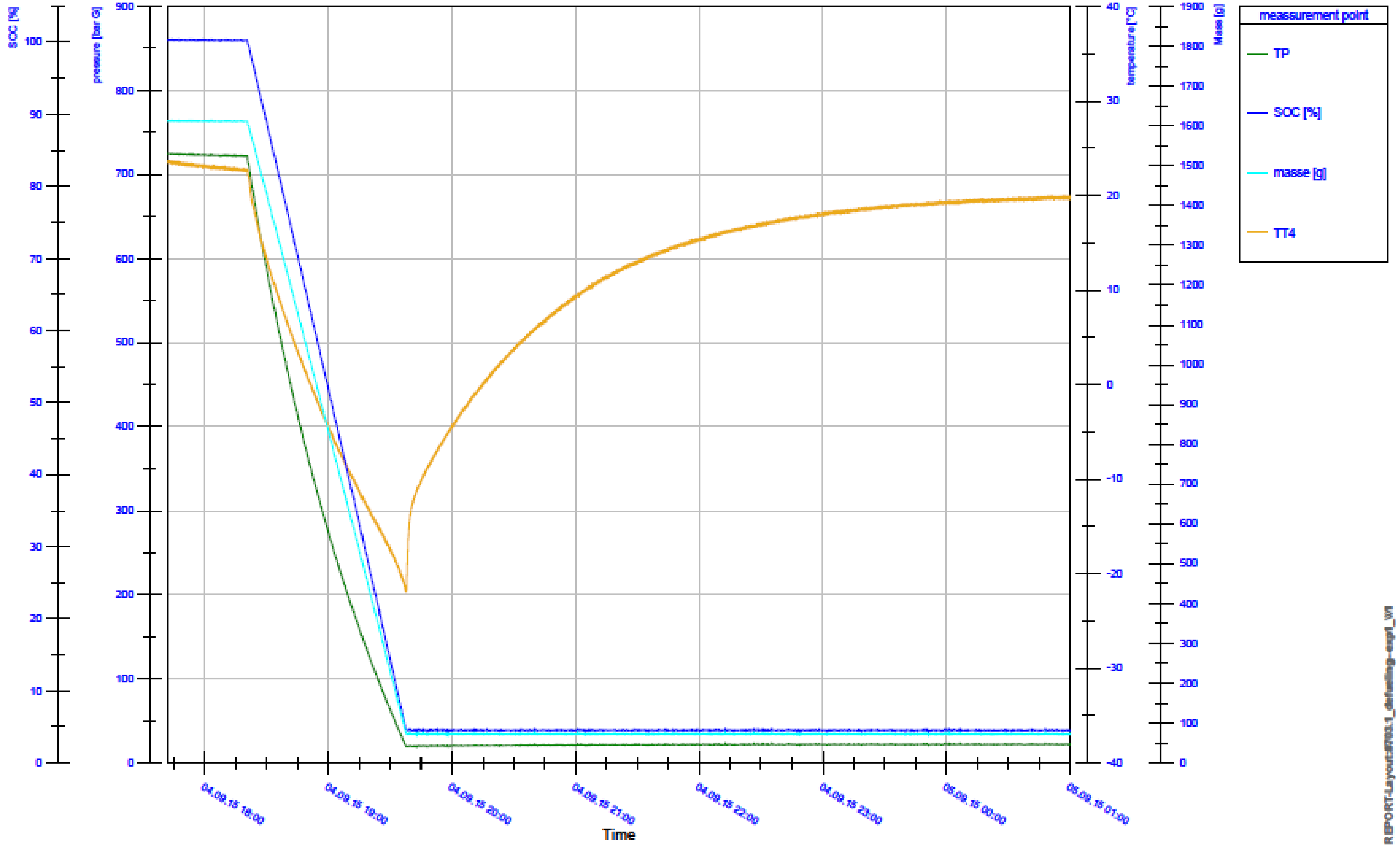

HyTransfer

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp3

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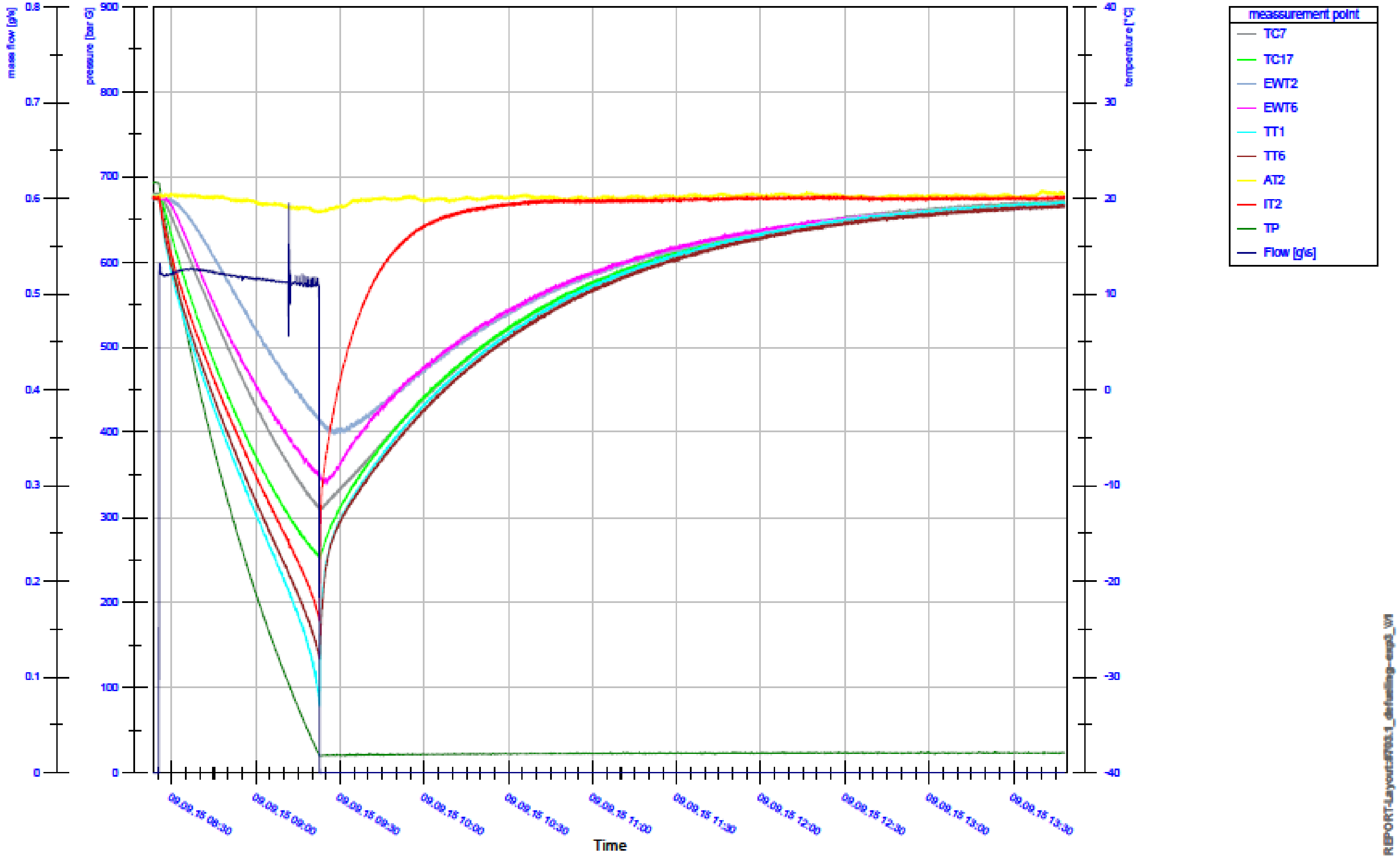


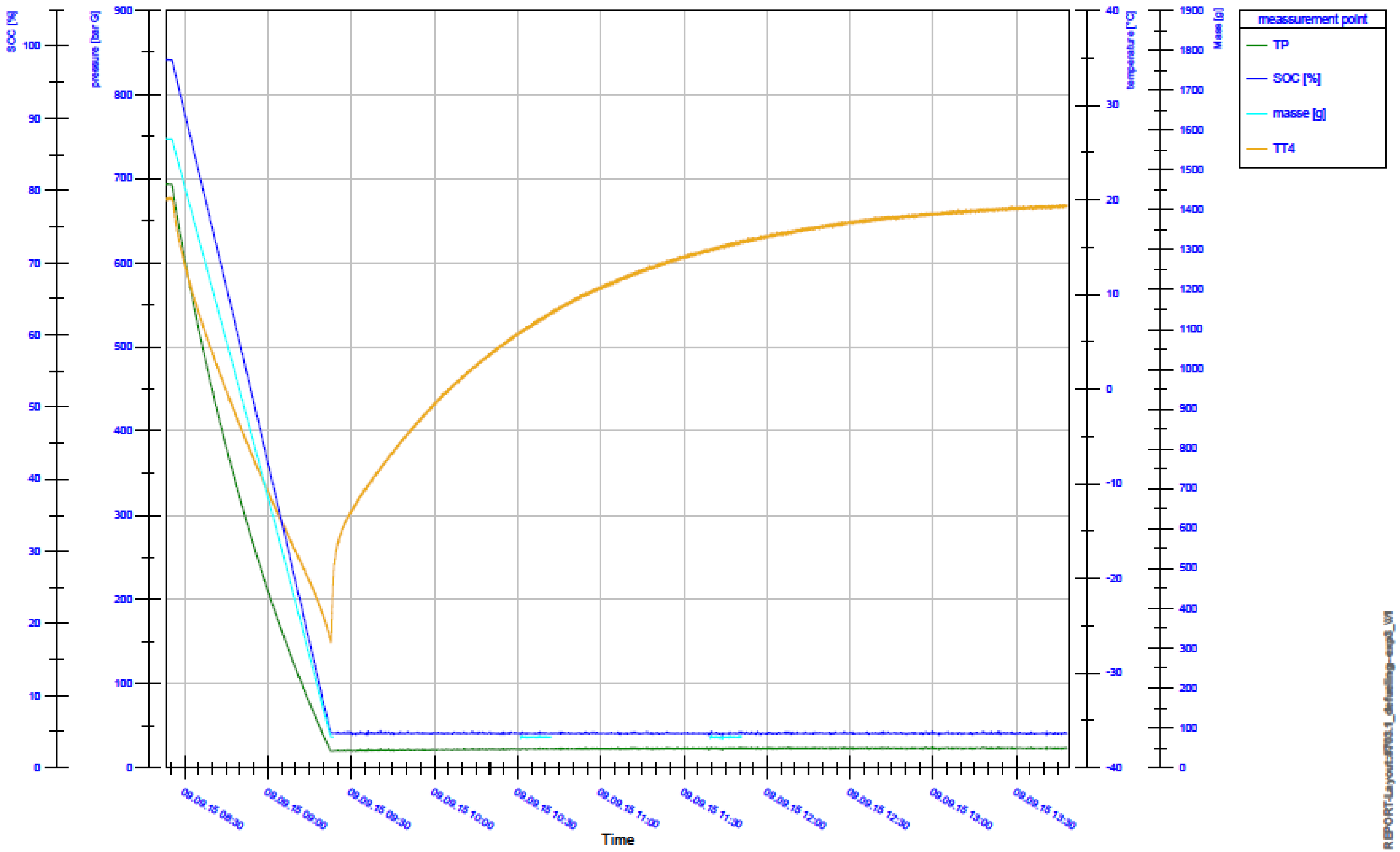
Project No. #703.1

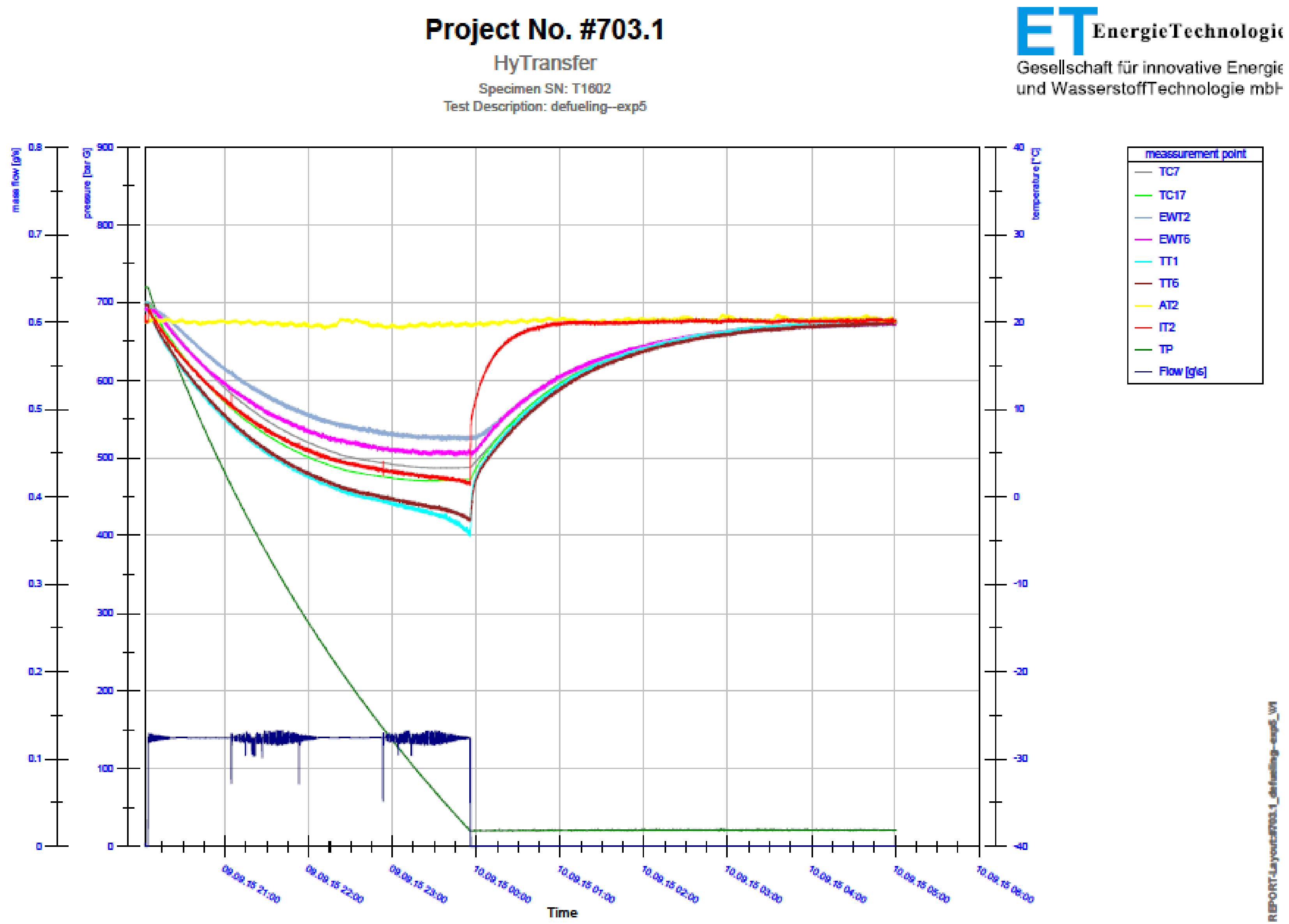
HyTransfer

Specimen SN: T1602

Test Description: defueling--exp3

ET EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH

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HyTransfer
Specimen SN: T1602
Test Description: defueling--exp5
EnergieTechnologie
Gesellschaft für innovative Energie
und WasserstoffTechnologie mbH
mass flow [g/s]
pressure [bar G]
temperature [°C]
measurement point
TC7
TC17
EWT2
EWT6
TT1
TT6
AT2
IT2
TP
Flow [g/s]
Time
09.09.15 21:00
09.09.15 22:00
09.09.15 23:00
10.09.15 00:00
10.09.15 01:00
10.09.15 02:00
10.09.15 03:00
10.09.15 04:00
10.09.15 05:00
10.09.15 06:00

Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp5

EnergieTechnologie
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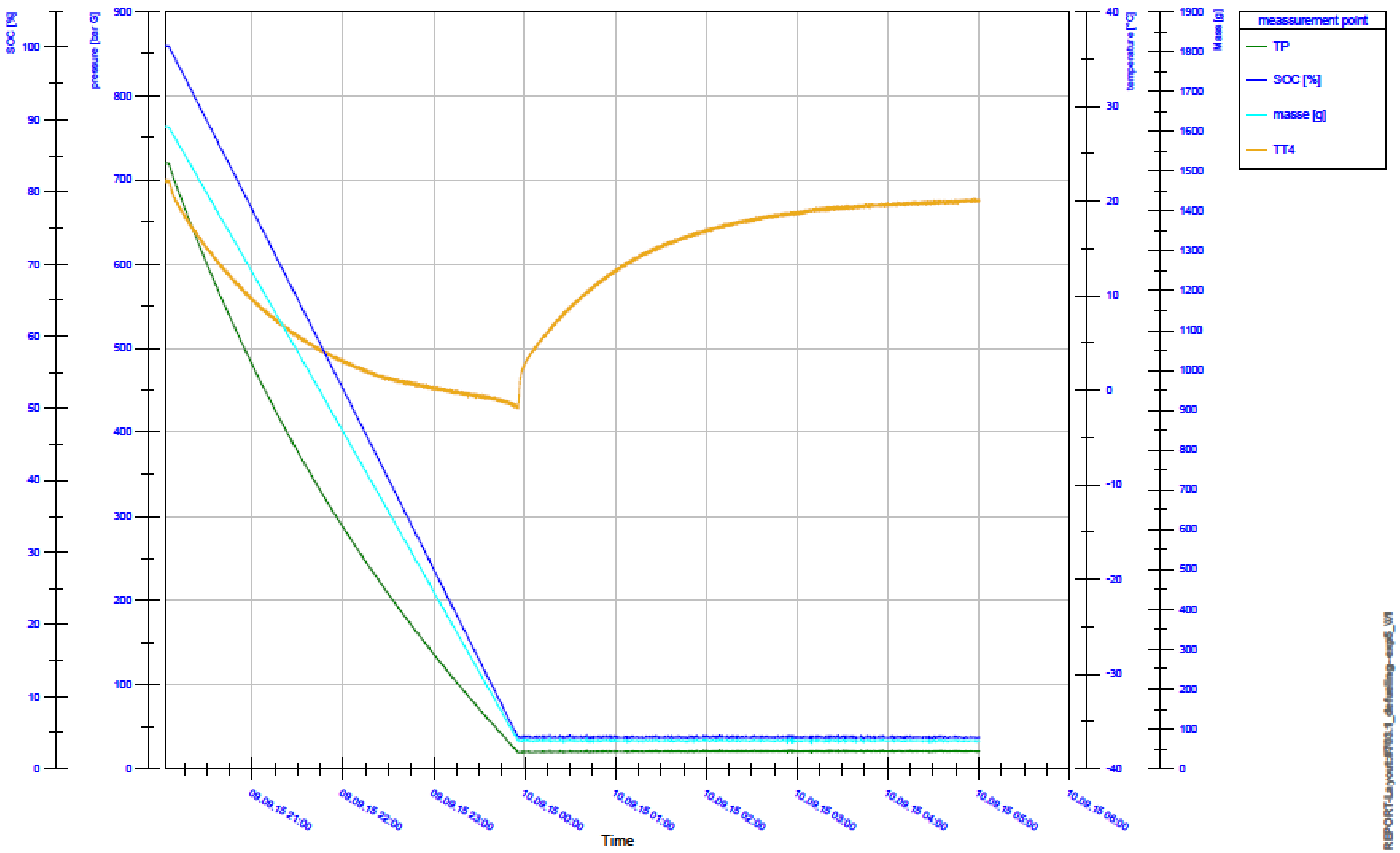


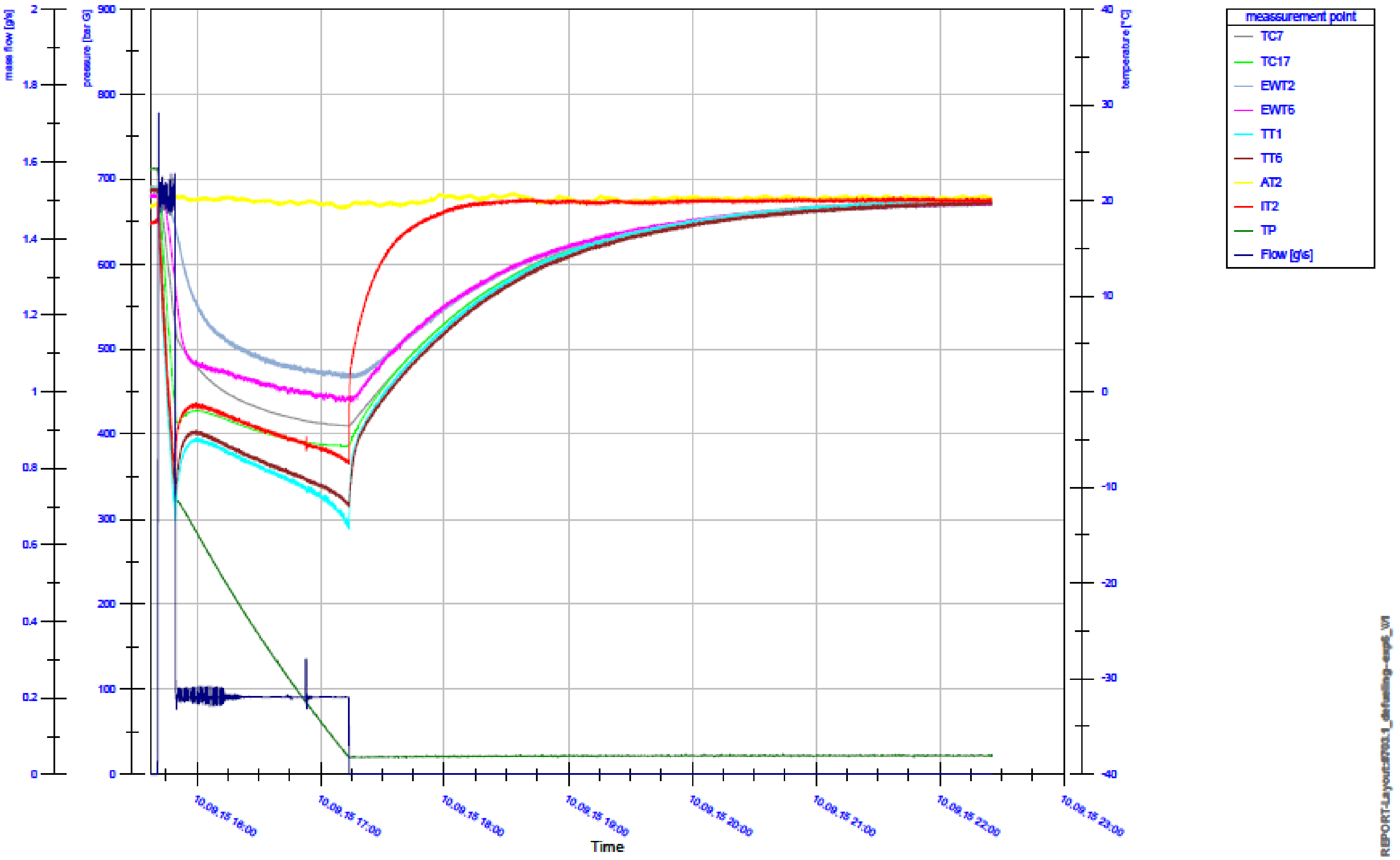
Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp8

Gesellschaft für innovative Energie und WasserstoffTechnologie mbH



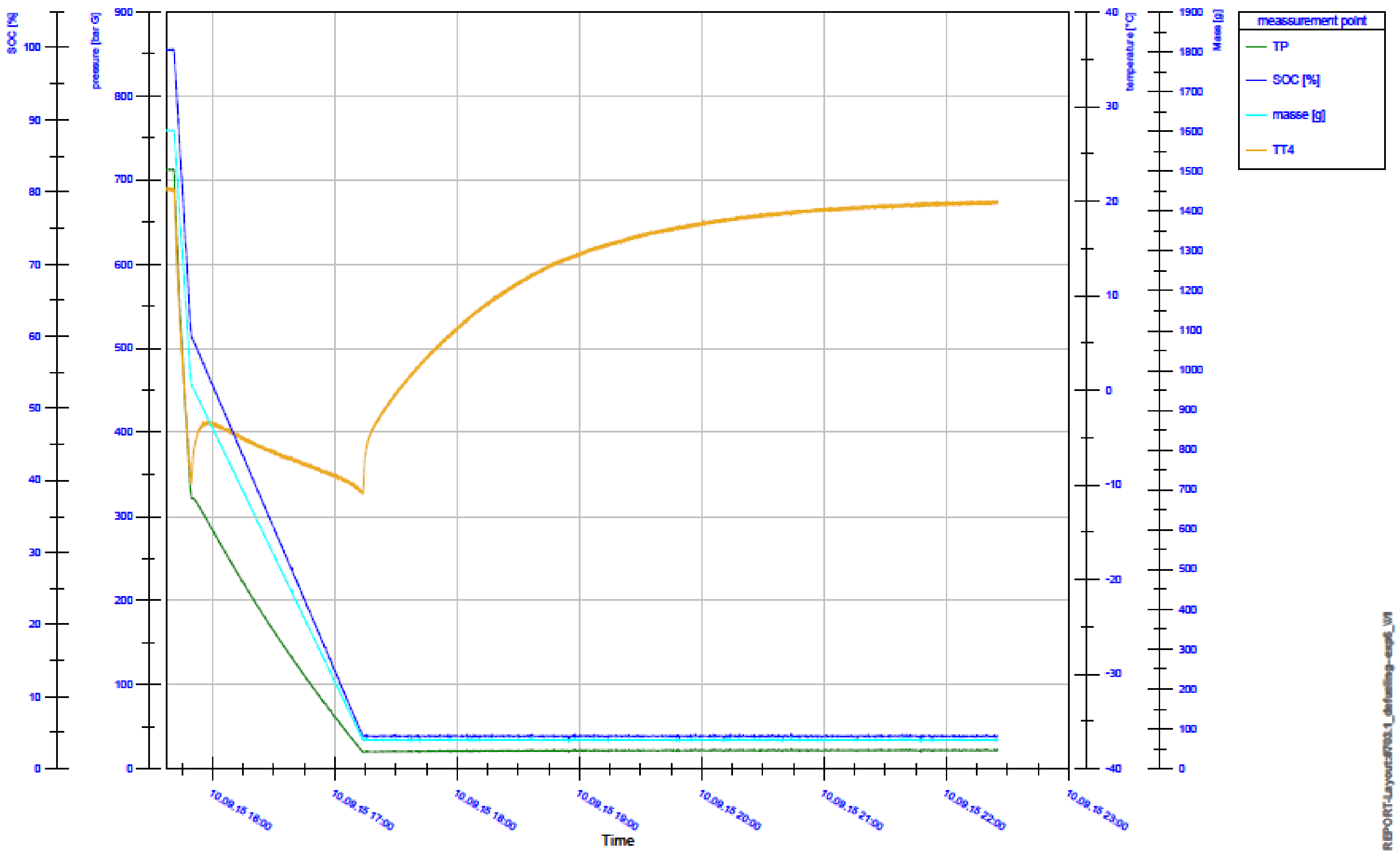
Project No. #703.1

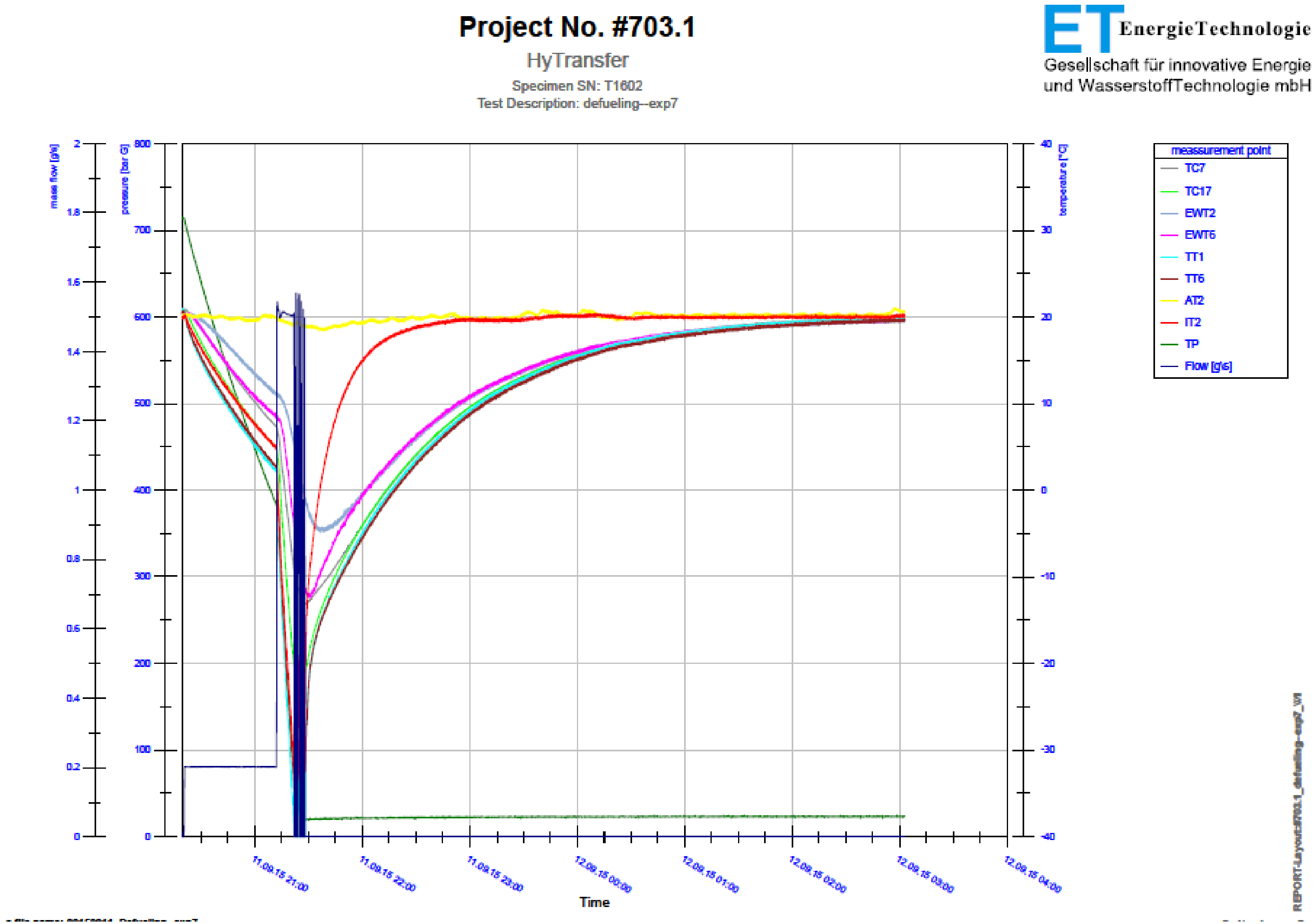
HyTransfer

Specimen SN: T1602

Test Description: defueling--exp6

ET EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH



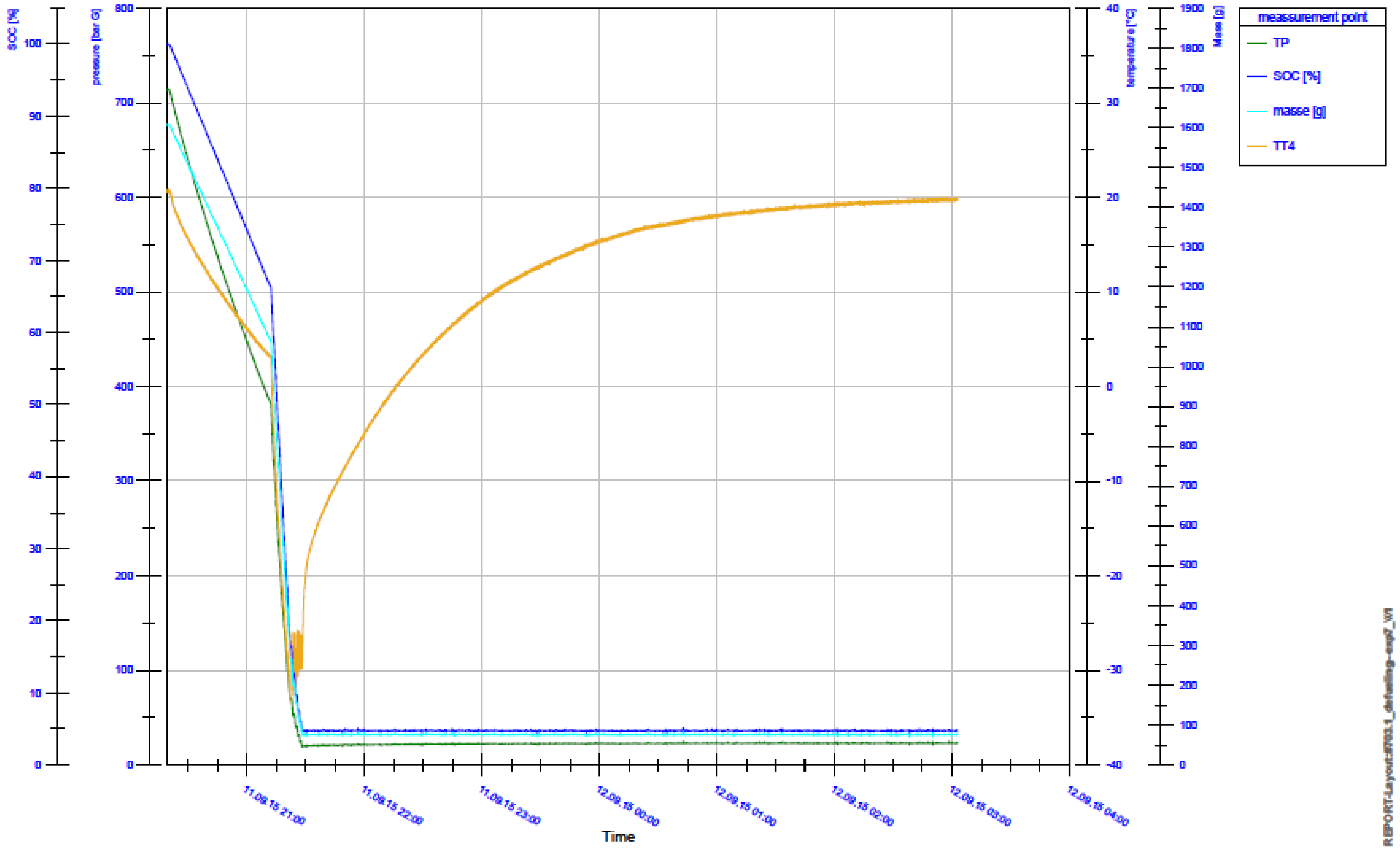

Project No. #703.1
HyTransfer
Specimen SN: T1602
Test Description: defueling--exp7
EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH
mass flow [g/s]
pressure [bar G]
temperature [°C]
measurement point
TC7
TC17
EWT2
EWT6
TT1
TT6
AT2
IT2
TP
Flow [g/s]
11.09.15 21:00
11.09.15 22:00
11.09.15 23:00
12.09.15 00:00
12.09.15 01:00
12.09.15 02:00
12.09.15 03:00
12.09.15 04:00
Time

Project No. #703.1

HyTransfer

Specimen SN: T1602
Test Description: defueling--exp7

EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH



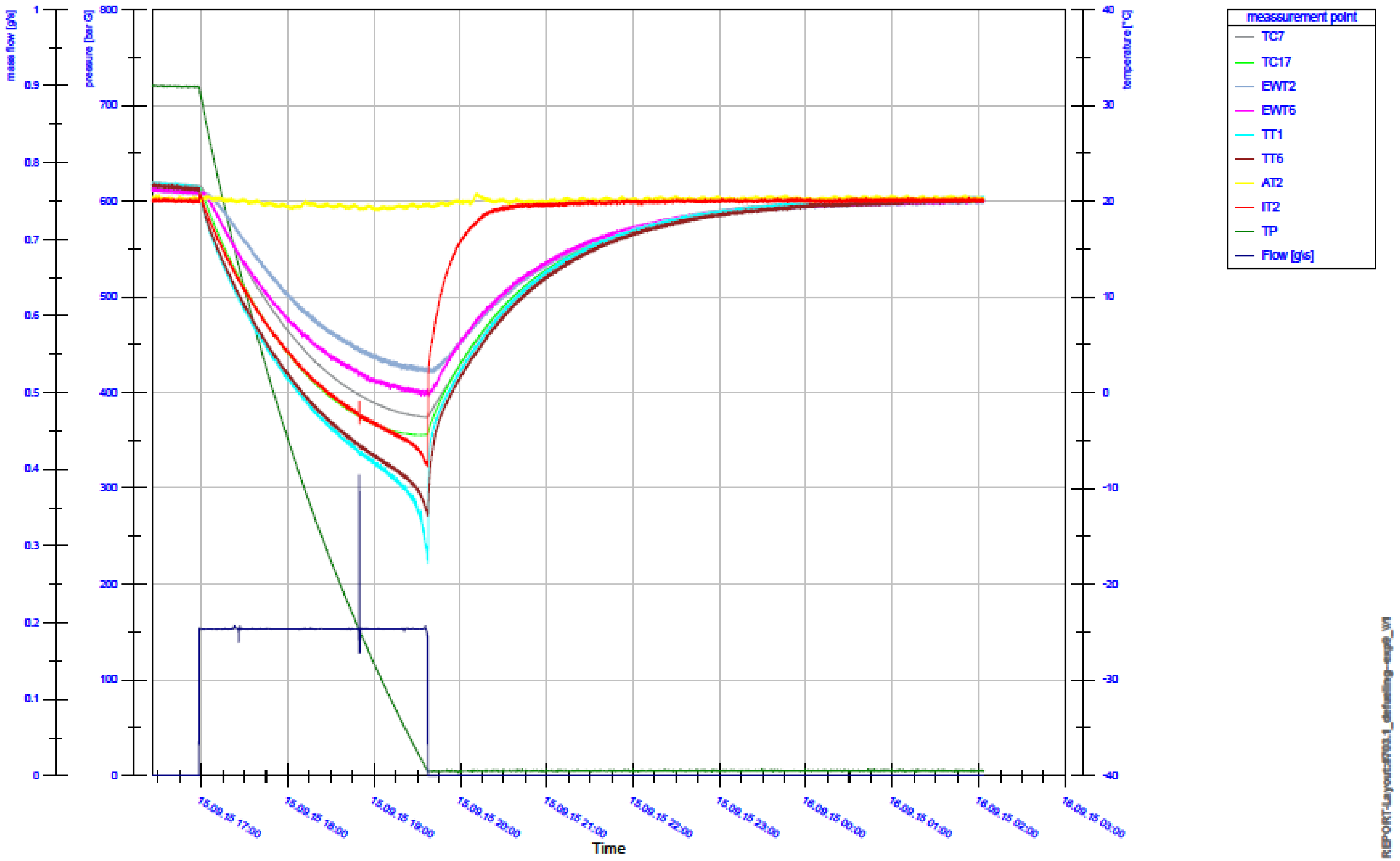
Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp9

ET EnergieTechnologie
Gesellschaft für innovative Energie und WasserstoffTechnologie mbH



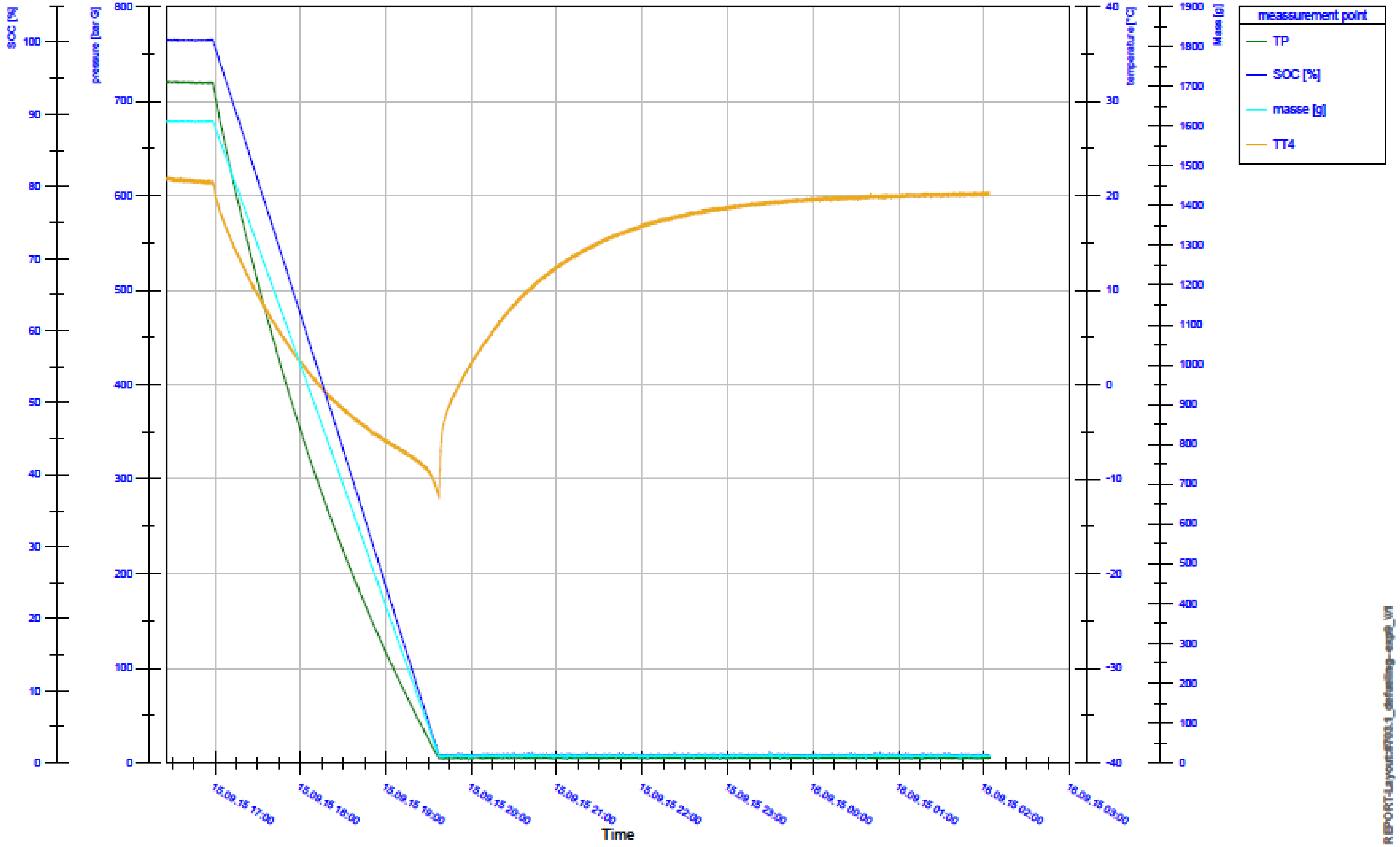
Project No. #703.1

HyTransfer

Specimen SN: T1602

Test Description: defueling--exp9

EnergieTechnologie
Gesellschaft für innovative Energie
und WasserstoffTechnologie mbH



Project No. #703.1

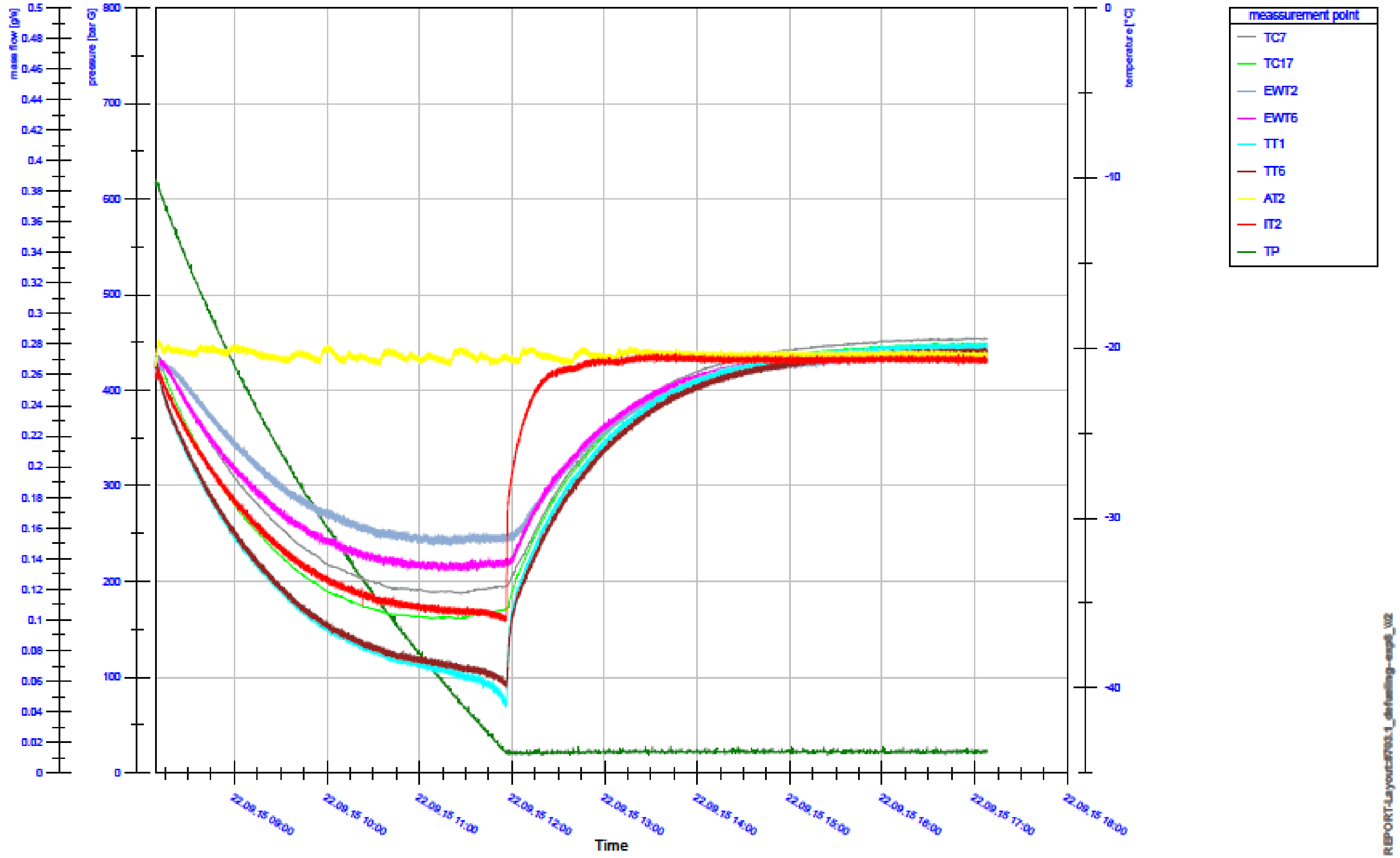
HyTransfer

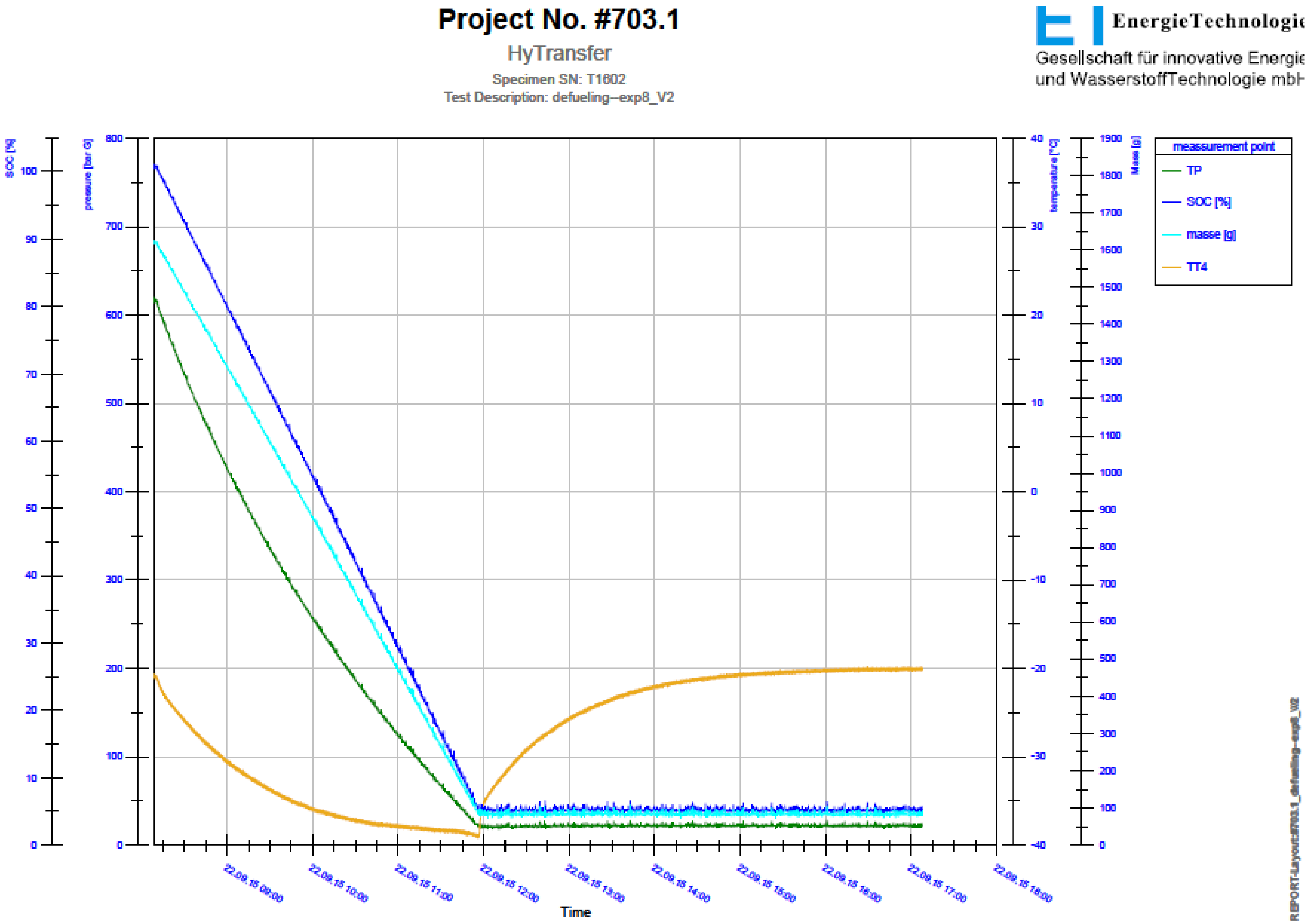
Specimen SN: T1602

Test Description: defueling--exp8_V2

EnergieTechnologie

Gesellschaft für innovative Energie und WasserstoffTechnologie mbH



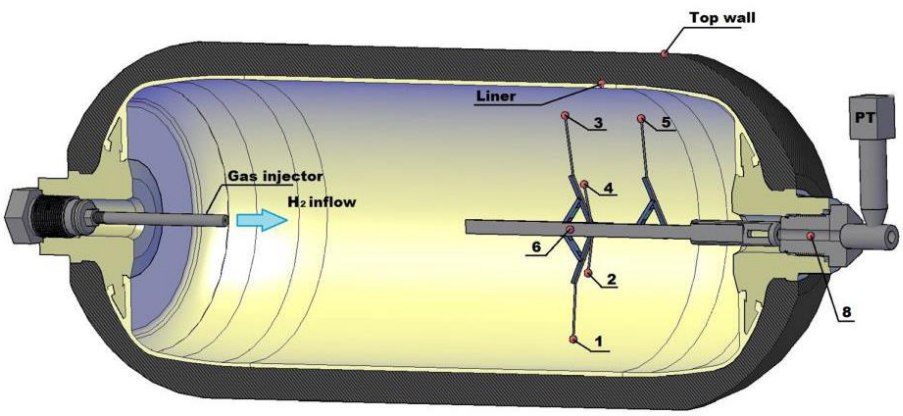


Project No. #703.1
HyTransfer
Specimen SN: T1602
Test Description: defueling--exp8_V2
EnergieTechnologie
Gesellschaft für innovative Energie
und WasserstoffTechnologie mbH
SOC [%]
pressure [bar G]
temperature [°C]
Masse [g]
meassurement point
TP
SOC [%]
masse [g]
TT4
Time
REPORT-Layout:#703.1_defueling--exp8_V2

6 CONCLUSION

To conclude we will summarize here the main learnings of experimental activities, raw data analysis and some crossed conclusions between the different laboratories

A set of 3 different tanks have been tested, representing different geometries and volumes as well as Type III (metallic liner with composite wrapping and Type IV (plastic liner with composite wrapping) tanks. In addition, to various instrumentation, including pressure, temperatures and flow measurements, the tanks were specially prepared with 30 thermocouples between the liner and the composite wrapping and a thermocouple tree, measuring the gas temperature in the different point of the tank, up to 10, was inserted. A set of injectors with different diameters helped to study the impact of the inlet speed in the tank. The figure below summarizes the uniquely instrumented tank configuration.

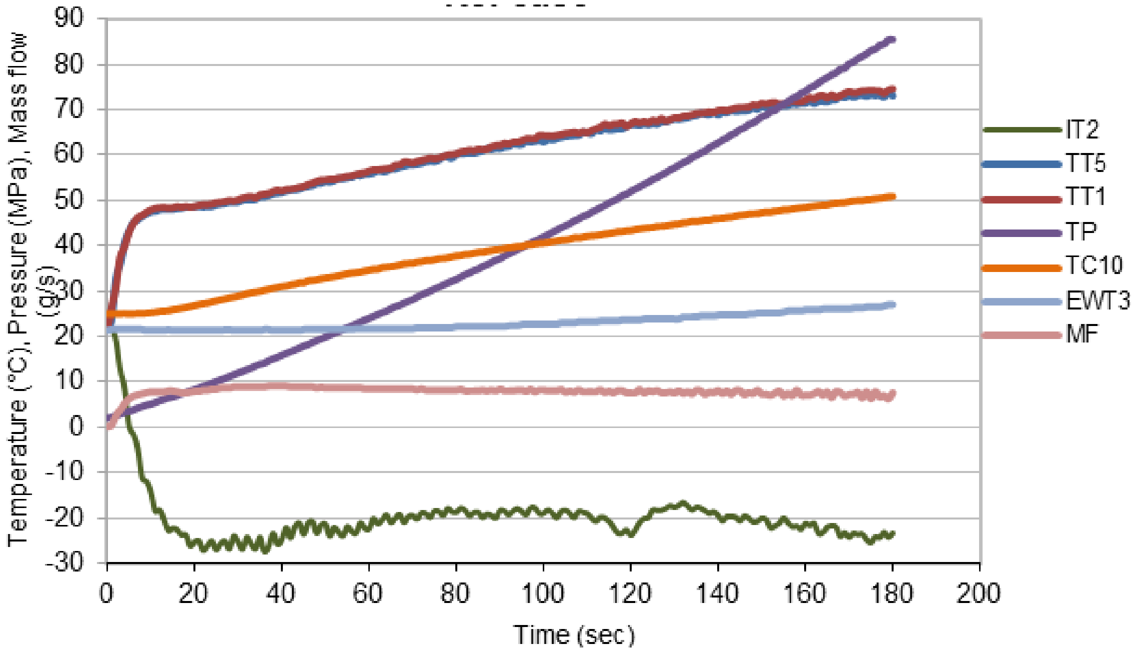


Insight of the tank instrumentation

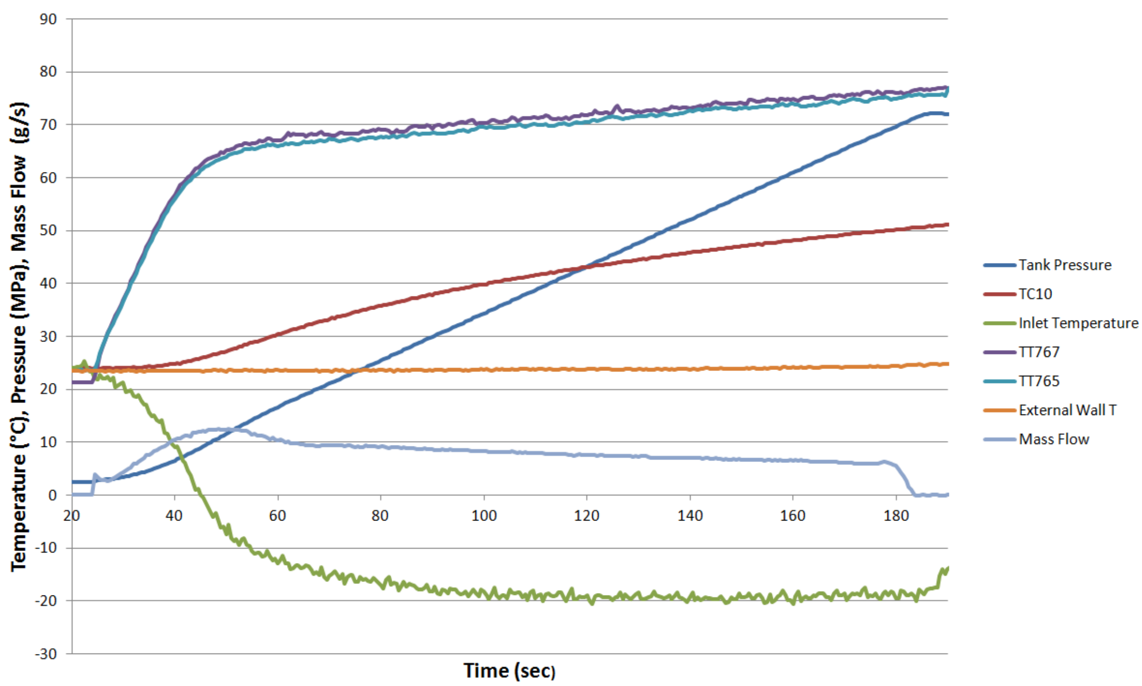
The system was tested following a test matrix, with varying parameters, including injection diameter, initial pressure, ambient temperature, pre-cooling temperature, mass flowrate and temperature profile. The tests were performed in 3 different laboratories including scientific and industrial installations. This was the opportunity to compare different way of performing the tests. A further experimental study would be to go in the details of the different parameters and for a first view we present here the reference case done for the 36l tank Type IV at JRC and AL-aT and the reference case done for the 40l tank Type III at JRC and ET.

1) For the first comparison between the Type IV reference cases, all parameters are equal, except the pre-cooling is slightly colder and the end pressure more important at JRC. The mass flow profile at AL-aT has a bit more important mass flow at the beginning when the pre-cooling is at its lowest. The pre-cooling at AL-aT takes about 30 seconds more to reach its target. At the end as some is these parameters are compensating, the final temperatures observed are within 3°C.

Reference case at JRC:



Reference case at AL-aT:

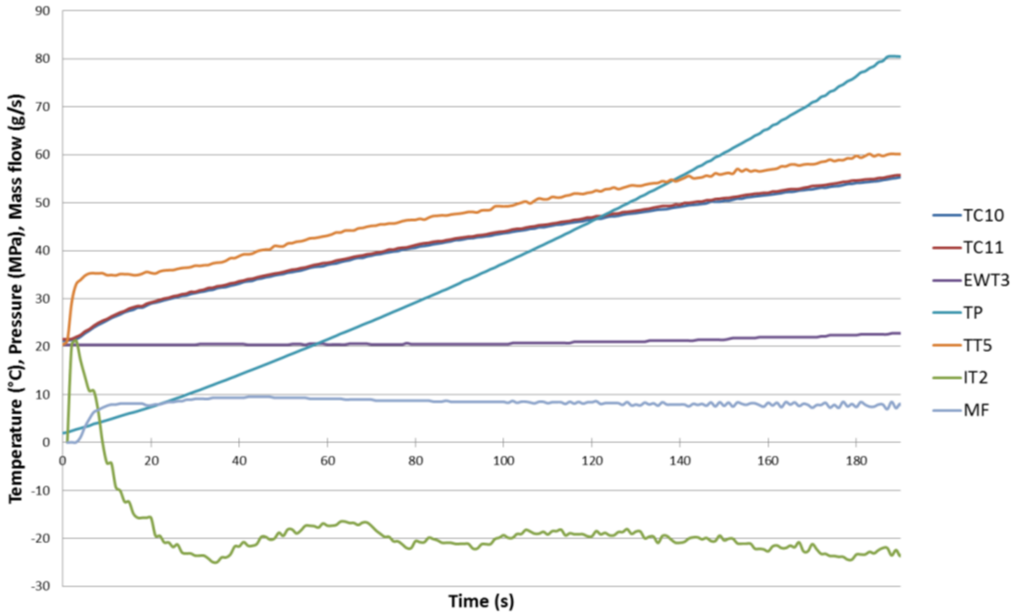


Laboratory	Final gas temperature	Final liner temperature	Ambiant temperature	Pre-cooling temperature	Final pressure
JRC	~74°C	~50°C	~20°C	~ -21°C	~870 bar
AL-aT	~77°C	~51°C	~20°C	~ -18°C	~730 bar

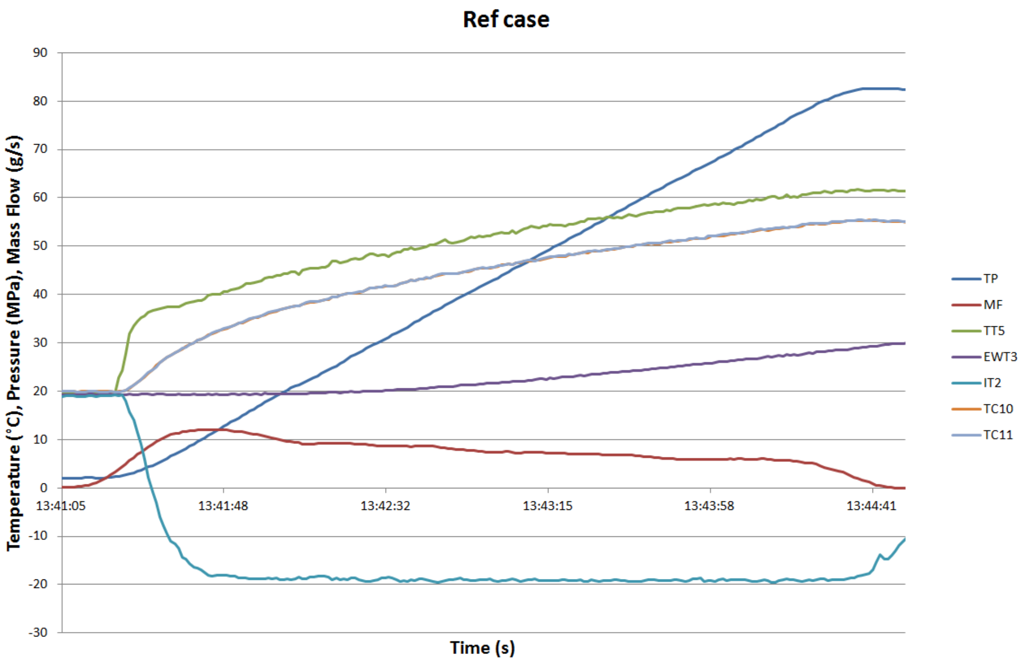
All other parameters are equal

2) For the second comparison between the Type III reference cases, all parameters are equal, except the pre-cooling is slightly colder at JRC and the end pressure a bit more important at ET. The mass flow profile at ET has a bit more important mass flow at the beginning when the pre-cooling is at its lowest. At the end, with very close parameters, the final temperatures observed are within 2°C.

Reference case at JRC:



Reference case at ET:



Laboratory	Final gas temperature	Final liner temperature	Ambiant temperature	Pre-cooling temperature	Final pressure
JRC	~60°C	~56°C	~20°C	~ -21°C	~800 bar
ET	~61°C	~56°C	~20°C	~ -19°C	~830 bar

All other parameters are equal

A deeper study would be necessary, but we can see on a first approach a good consistency between the different test laboratories.

All the data were then processed through CFD and simple model simulations, to confirm and adjust the models parameters. Once this model validation step completed, the next step of the project, in Work Package 5, was to build a test bench “vehicle like” to include more parameters to the protocol testing.

This Work Package 4 experimental campaign was a successful testing of uniquely instrumented tanks in various facilities for model validation.