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1,000+ cycles of a 350 bar prototype cryo-compressed pressure vessel

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Disclaimer

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1,000+ fills of a 350 bar prototype cryo-compressed pressure vessel

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Abstract

A type 3 pressure vessel similar to the vessel used in their prototype cryo-compressed vehicle was leased by BMW AG (Munich, Germany) to Lawrence Livermore National Laboratory (Livermore, CA) in order to conduct multiple cryo-compressed fills at the testing facility, using the Linde 900 bar LH_2 pump. The prototype vessel was installed in the containment vessel and filled more than 1,000 times to 300 bar with the pump, and underwent a few excursions up to 350 bar to simulate long-term parking. The test started in April 2017 and ended in March 2018, although its suffered a significant delay as the LH_2 pump experienced a major failure on April 19th 2017 and was returned to Germany for repair. The LH_2 pump was re-commissioned in January 2018, and cycling was resumed on February 6th, 2018. At the time this report is being written, the vessel is still installed in the containment vessel and pressurized with H_2 at around 350 bar, simulating long-term parking (multiple months) at maximum rated pressure. No failure of the prototype pressure vessel could be observed over the length of the testing period: no catastrophic failure, no measurable H_2 leak nor loss of vacuum inside the containment vessel, no leak at maximum rated pressure with room temperature H_2 after 1,000+ pressure cycles. In this report, we present the major results of this effort, including data from the LH_2 station concerning electricity consumption, boil-off and pump outlet temperature.

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Introduction

Liquid hydrogen (LH_2) has many benefits for the hydrogen infrastructure: its high density allows minimum costs for distribution (e.g. $167/kg H_2 for a liquid trailer vs. $783/kg H_2 for a gaseous trailer [1]) and stationary storage, its high payload and short transfer times ease delivery logistics, its low temperature provides very low potential burst energy [2], and LH_2 pumps can efficiently achieve large throughputs with a small footprint (low electricity consumption and compact designs).

Those benefits translate into significant capital and operational expenses reduction for hydrogen refueling station owners and operators. For example, **Figure 1** shows the initial installed capital expenditure for various 4,000 kg/day hydrogen refueling station designs: the first 3 rely on LH_2 delivery, while the last 2 rely on gaseous delivery. All assume gaseous ambient 350 bar storage onboard the Fuel Cell Electric Vehicles – FCEV (capacity: 50 kg), except the first one (“CcH_2” or cryo-compressed H_2 [3],[4]) that assumes cryogenic storage at 350 bar. As such, the fuel is directly dispensed to the FCEV (no cascade, no evaporator). Also, the first two scenarios (from left) use a LH_2 pump, and the third scenario uses a compressor that vaporizes the LH_2 before compressing it. The major cost differences come from the cost of the LH_2 pump vs. compressor (red bars) and the bulk storage (blue bars). Please note that the outcomes from the model [5] have been slightly modified for the fourth scenario: the cost of the gaseous delivery tube trailer(s) was added to the “bulk storage” cost as such a large station would need to have trailers dedicated only to that station. **Figure 2** highlights the cost difference of installed compressors and LH_2 pumps in $2016/(kg/hour) for 3 different production volume assumptions (low, mid and high). At 350 bar, compressors are 2.7 times more expensive than LH_2 pumps to achieve the same throughput. This ratio becomes 3.4 at 700 bar.

The benefits of LH_2 distribution are illustrated in a California Air Resources Board (CARB) report [6], that analyses future deployment of H_2 fueling stations for different sources of H_2 (liquid or gaseous delivery, or on-site SMR). CARB anticipates that, regardless of the rate of FCEV introduction, most fueling stations will be supplied with LH_2 in the future. Indeed, LH_2 distribution is particularly favorable as station size increases. For example, the largest fleet of H_2 buses in the world (AC Transit [7] in Oakland, CA) uses LH_2, and most of the ~40 FC forklift refueling stations in the U.S. are relying on LH_2 supply.

BMW AG has been working on the LH_2 pathway for more than 2 decades, including unique developments in the field of cryo-compressed pressure vessels. One important gap in cryo-compressed R&D is the lack of data concerning the cyclability of the storage system, that undergoes many pressure cycles over wide range of temperatures. Pursuing the long-standing collaboration between LLNL and BMW AG, a pressure vessel was leased by the car company to LLNL in order to perform cryogenic cycle testing. This report presents the main results of this effort, including details on the experimental test bench (Section 1), vessel cycle testing (Section 2), LH_2 pump performances (Section 3) and the pump failure that was experienced (Section 4).

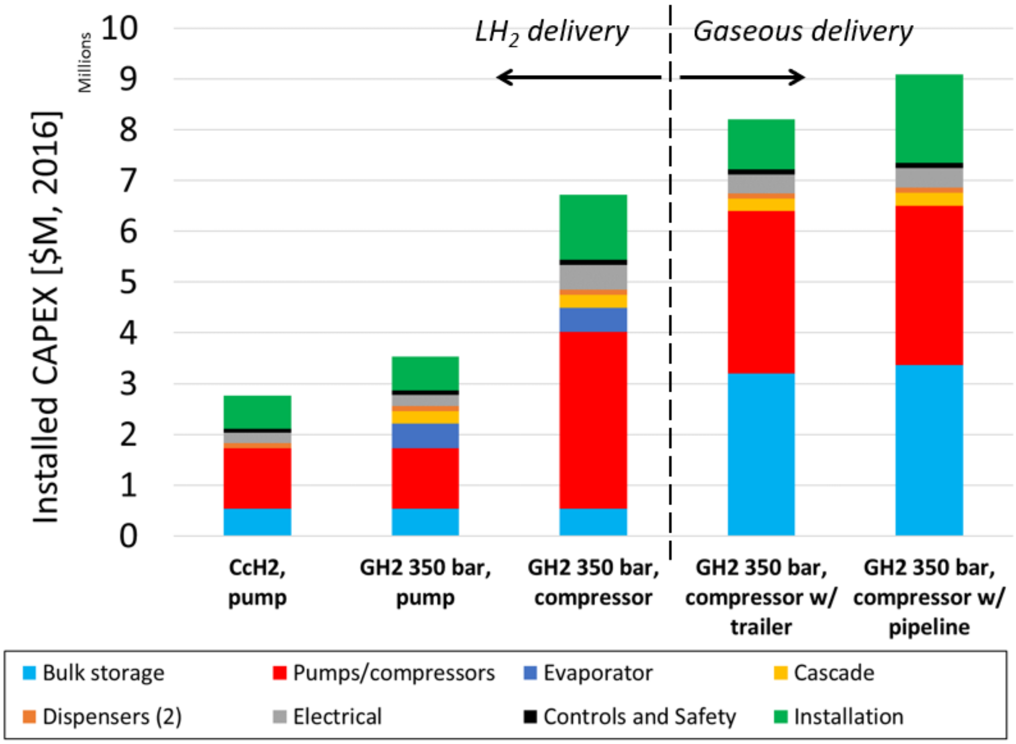


Figure 1: Projected installed capital expenditures in $2016, for a 4,000 kg/day hydrogen refueling station (FCEV capacity: 50 kg H_2) computed from HDRSAM V1.0 [5], assuming high production volume.

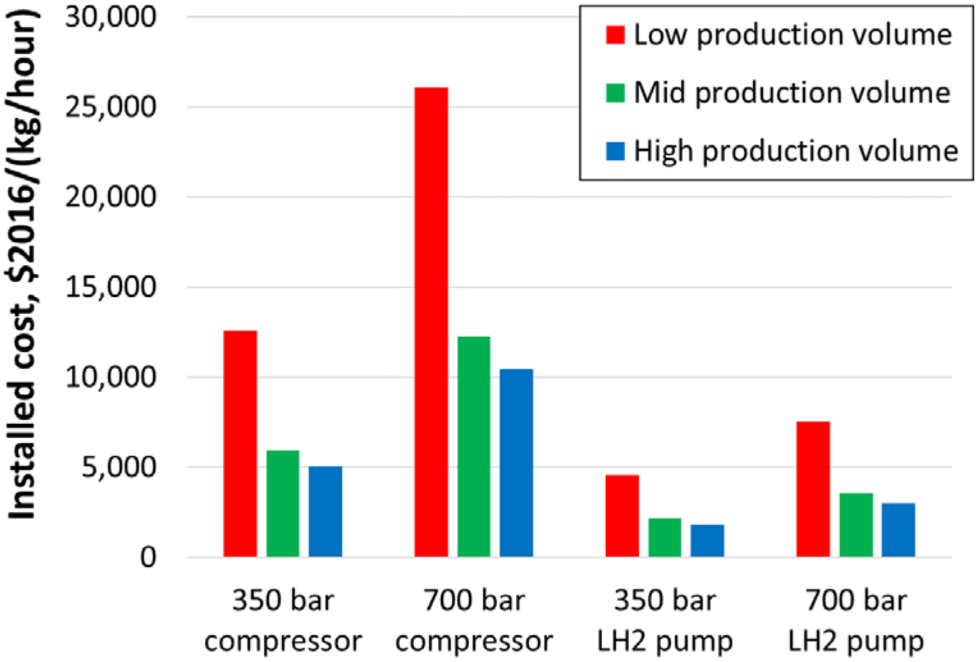


Figure 2: Projected installed cost of 350 and 700 bar compressors and LH_2 pumps in $2016/(kg/hour), as computed from HDRSAM V1.0 [5], for different production volumes (low, mid and high). Compressors are 5 stages with a 3 bar suction pressure. Flow rates for compressors and LH_2 pumps are 35 and 120 kg/hour, respectively.

1. Description of the experimental setup

LLNL's Hydrogen Test Facility has been built over the last five years at the south end of the campus (**Figure 3**) and includes an 875 bar liquid hydrogen pump manufactured by Linde, a liquid hydrogen Dewar with capacity for 12.5 m^3, a 3 m^3 containment vessel rated for 65 bar maximum pressure; two vent stacks (one for high pressure discharge rated for up to 250 g/s, and one for low pressure), a control room for remote operation, connecting high pressure cryogenic lines (rated at 1,400 bar), air operated actuated cryogenic valves (rated at 2,000 bar) and instrumentation for temperature, pressure, hydrogen level, electricity consumption, and vacuum.

We next describe the key system components.

Figure 3: LLNL's Hydrogen Test Facility.

1.1. Liquid hydrogen pump

The LH$_2$ pump takes liquid hydrogen from the station Dewar at low pressure (3 bar absolute) and very low temperature (24.6 K) and delivers it as a cryogenic compressed gas at pressures as high as 875 bar and temperatures between 30 and 60 K. The basic operation of the pump is illustrated in **Figure 4**. The pump operates immersed in LH$_2$ (colored in blue) inside a secondary Dewar (the pump Dewar), which fills by gravity with LH$_2$ from the station Dewar. When the piston moves down, a valve opens allowing hydrogen to flood the main cylinder. Upward movement of the piston compresses the hydrogen in the main cylinder to a moderate pressure (6 bar), sufficient to remove the LH$_2$ from near saturation into a thermodynamic state far removed from saturation that is unlikely to cavitate. The piston shaft is hollow, enabling hydrogen to flow from the main cylinder into the second stage of compression, where the piston pressurizes the hydrogen to the vehicle vessel pressure, up to 875 bar. The hydrogen flows through a check valve into the vehicle vessel.

The pump speed profile during a typical fill is illustrated in **Figure 5**. The pump starts slow (10% of maximum speed), and then ramps up to a steady speed – likely (although not necessarily) the maximum pump speed (1.44 Hz). The pump slows down to 10% of maximum speed when the target fill pressure is approached, and it automatically shuts down when the target pressure is reached. Hydrogen flow rate varies linearly with pump speed up to ~70% of maximum, and then levels off and increases little up to maximum speed.

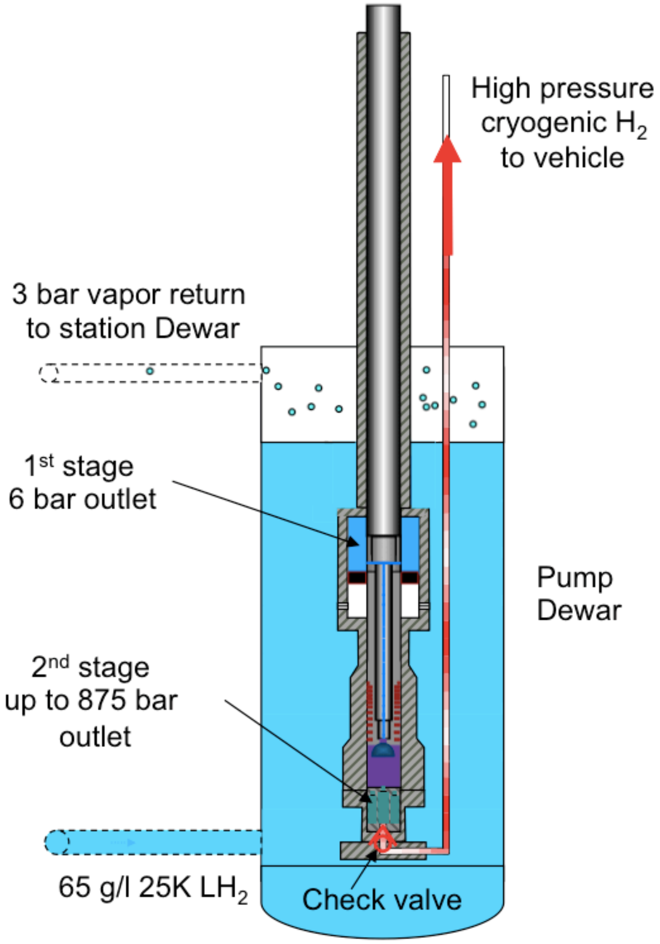


Figure 4: Schematic describing operation of liquid hydrogen pump.

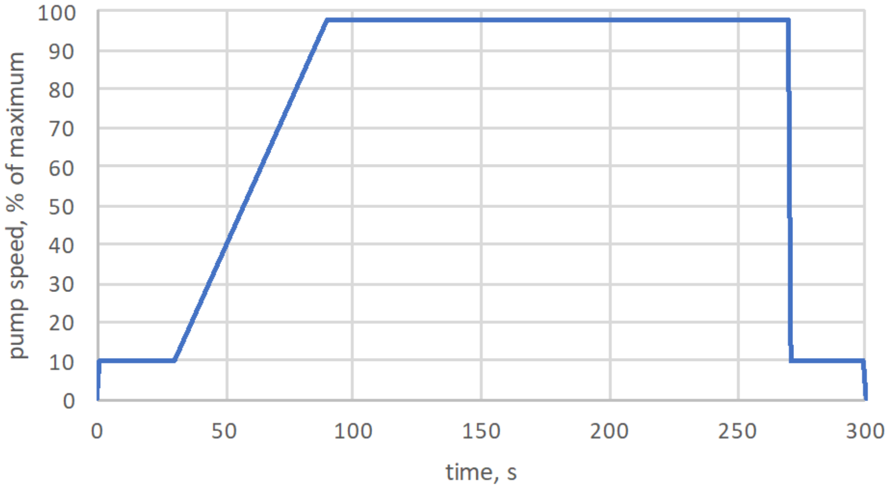


Figure 5: LH_2 pump speed evolution during a typical fill cycle.

From the pump speed profile of **Figure 5**, it is apparent that there is a difference between average and maximum H_2 flow rates, and the difference depends on the fraction of time the pump spends at low speed vs. maximum speed. Initial slow operation time and ramp rate are adjustable, and careful tuning of these parameters can increase average fueling rate while still allowing gradual pump speed-up, thereby minimizing piston stresses and lengthening maintenance intervals.

The LH_2 pump offers fundamental thermodynamic advantages over today's technologies that compress gaseous hydrogen (typically into a cascade) before dispensing:

1. Higher LH_2 density than gaseous hydrogen maximizes throughput and minimizes compression work [8]
2. Fill directly from the pump without the expenses and losses of intermediate high-pressure buffer storage (cascade)
3. Direct fills means that hydrogen is pressurized between the initial pressure in the vehicle vessel and up to near its rated pressure, thus increasing the durability of the pump (less pumping at maximum pressure)
4. Fill speed is not limited by hydrogen heating
5. No need for hydrogen refrigeration or precooling at the station

These thermodynamic advantages result in practical advantages vs. today's alternative technologies for hydrogen refueling:

- High throughput, 100+ kg/h
- Low station footprint and capital cost [1]
- Low electricity consumption due to high density of LH_2 minimizing compression work
- Highest fill density, up to 80 g/L (estimated) when dispensing cryogenic hydrogen
- No limitation on station availability (no buffer or pre-cooling), infinite "*back-to-back*"

The liquid hydrogen pump has the capacity for rapid (<5 minute) inexpensive refueling of vehicles with both ambient temperature (by running the hydrogen through a heat exchanger) and cryogenic vessels and it is ideal for large stations demanding many consecutive refuels. Beyond automobiles, other vehicles such as buses, medium/heavy-duty vehicles, rail, marine, and aircraft can benefit from the high-density hydrogen storage while avoiding the need for precooling during refueling.

1.2. Station LH_2 Dewar

The station Dewar has a total inner volume of 12.5 m^3 and its maximum LH_2 level is set by the try-cock valve at 11.35 m^3. The relief pressure under normal operation is set at 3 bar. Depending on stratification in the Dewar (which may be significant since it is vertical), the density of LH_2 in the Dewar can be between 70 kg/m^3 (saturated at atmospheric pressure) and 65 kg/m^3 (saturated at 3 bar), thus the maximum LH_2 capacity is between 740 and 800 kg. In practice, the station Dewar could only be filled to about 80% of the theoretical try-cock value, therefore the maximum capacity is 600-640 kg LH_2.

1.3. Containment Vessel and Vent Stack

Another key component of LLNL's Hydrogen Test Facility is a containment vessel (**Figure 6**) that enables testing of experimental pressure vessel prototypes not certified by current standards (ASME, ISO, FMVSS) and therefore cannot be tested in manned area operations. Made of 3.2 cm thick stainless steel 304 and weighing almost 5,000 kg, the containment vessel is rated for 65 bar maximum pressure and can contain the equivalent energy of 1.8 kg of TNT, therefore enabling testing of full-scale vessels and hydrogen systems. The containment vessel can also hold vacuum down to 1 Pascal. A 9-meter high vent stack enables rapid venting of hydrogen after pressure testing. High altitude venting of hydrogen is recommended by the Compressed Gas Association standards for rapid dispersion away from personnel and equipment at ground level.

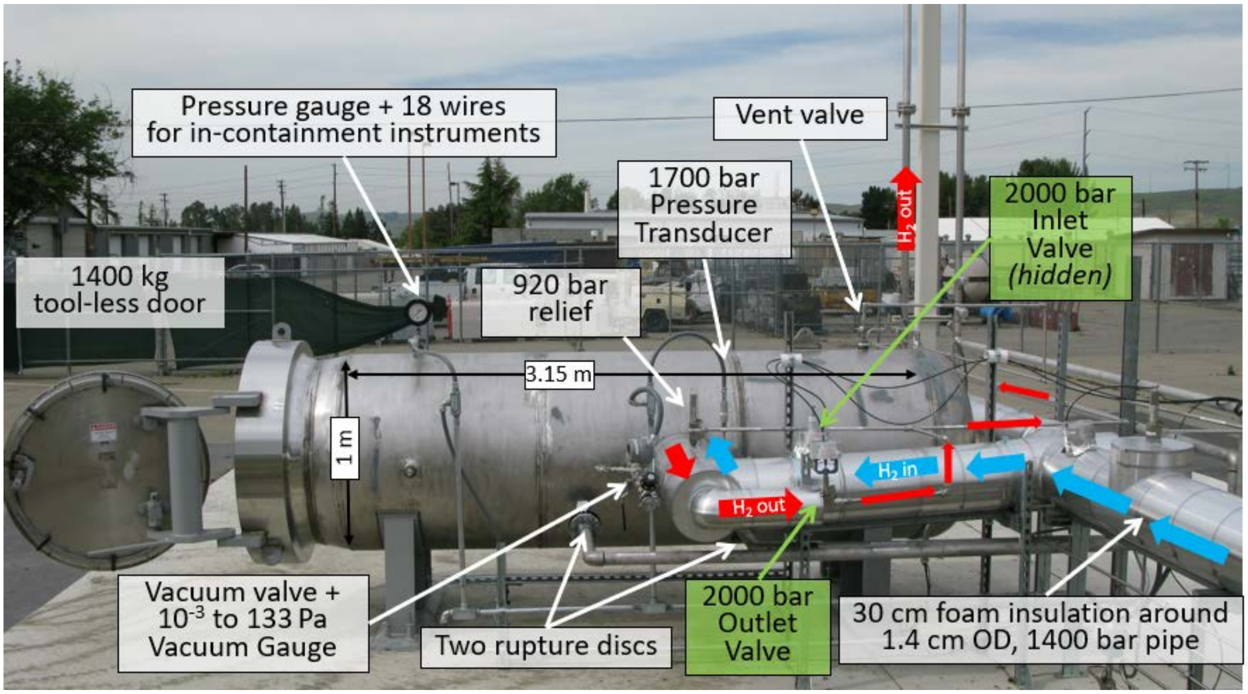


Figure 6: Containment vessel including piping and instrumentation details. The containment vessel is located on the 9 m x 9 m concrete test pad and is remotely operated from the control room.

1.4. Control Room and Instrumentation

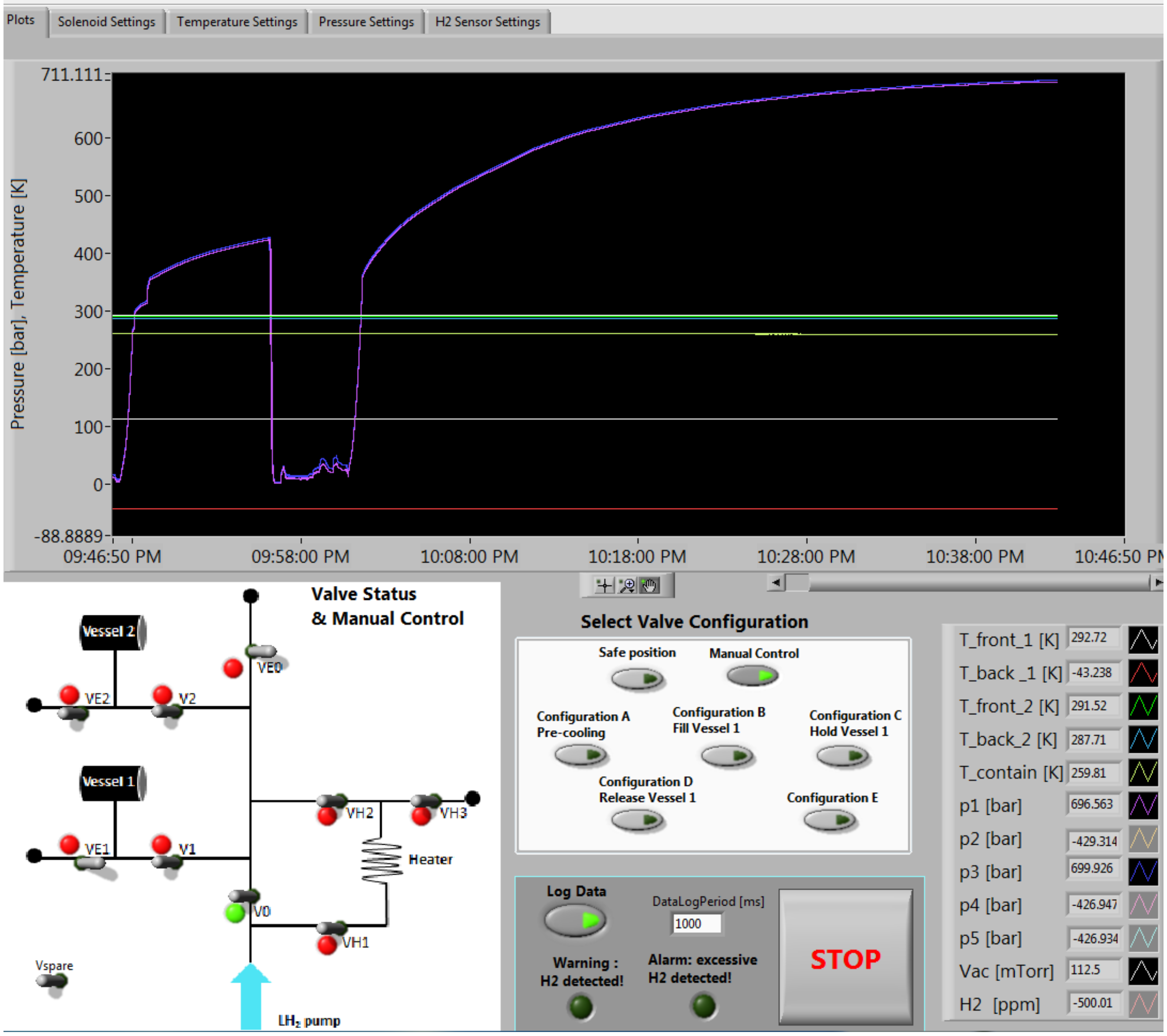
Experiments can be operated from a control room strategically located for maximum visibility and far enough from the Dewar (23 meters) to meet National Fire Protection Association standards. Full instrumentation (**Table 1**) is also available to monitor all aspects of the operation. All sensors located in the LH_2 pump room and on the 9-m x 9-m concrete pad are explosion-proof (Class 1 Division 1 group B).

The facility can be operated by a single person from the control room, using a Siemens interface for the pump controls and a LLNL-developed LabVIEW interface for the test pad controls. Cryogenic high-pressure (2000 bar) pneumatic valves are remotely operated using 7 bar air. **Figure 7** shows a screenshot of the LabVIEW control panel: data are plotted on the upper part of the screen, while valves can be operated using either the interface located at the bottom left or the pre-programmed configurations from the middle panel.

Table 1:LLNL's Hydrogen Test Facility instrumentation.

Facility component	Measured experimental data
Station Dewar	• Liquid hydrogen level (0-2500 Pa) • Vapor pressure (1-7 bar absolute) • Boil-off (0-10 kg/hr)
LH_2 pump	• Outlet pressure and temperature (0-900 bar, 20-330 K) • Pump frequency (0-2 Hz) • Active and apparent electric energy and power

	• Hydrogen concentration in pump room (for safety) • Vibration (for earthquake detection)
Pump Dewar	• Liquid hydrogen level (0-100%) • Pressure (1-7 bar absolute) • Temperature (20-330 K)
Test vessel	• Pressure and temperature(s) (0-1700 bar, 20-330 K)
Containment vessel	• Vacuum (10^{-3}-133 Pa) • Hydrogen concentration (0-2,000 ppm)



DataLogPeriod [ms] 1000

T_front_1 [K] 292.72
T_back _1 [K] -43.238
T_front_2 [K] 291.52
T_back_2 [K] 287.71
T_contain [K] 259.81
p1 [bar] 696.563
p2 [bar] -429.314
p3 [bar] 699.926
p4 [bar] -426.947
p5 [bar] -426.934
Vac [mTorr] 112.5
H2 [ppm] -500.01

Figure 7: Screenshot of control room data acquisition system implemented in LabVIEW.

The boil-off sensor measures H_2 mass flow leaving the station Dewar through the vent stack. This is the regular station boil-off path during both pump idle and operation. Another boil-off path exists that comes directly from the LH_2 pump Dewar, and is used when the level of LH_2 in the pump Dewar (Figure 2) is too low (below 80%). This second path is not instrumented and will be discussed later in the paper.

Electric power and energy consumed by the pump motor are measured using a power analyzer that records active and apparent power and energy, voltage, current and phase angle of each of the three phases. The total electric power is the root sum of squares of the active and reactive powers: it is called "apparent" power and is measured in Volt-Amperes (VA). The active (or real or true) power is drawn by the electric resistance of a system doing useful work, and is measured in Watts (W). The reactive power does no work on the load, it is stored in and discharged by inductive motors, transformers or solenoids, and is measured in Volt-Amperes Reactive (VAR).

The LH_2 pump room is equipped with a variety of sensors. Pressure, temperature and level sensors inside the pump Dewar are used for controlling the cool-down process and the level of LH_2 during operation. Pump outlet pressure and temperature are used to estimate the thermodynamic state of the H_2 leaving the pump, and the pump speed is used to set the flow rate. In addition to this, H_2 and vibration sensors are also installed but used only for emergency and not recorded.

The test pad is also equipped with pressure and temperature sensors to estimate the thermodynamic state of the H_2 entering the test vessel, while a vacuum transducer and H_2 sensor are connected to the containment vessel to detect leaks and ensure safe operation.

1.5.Prototype pressure vessel

The prototype vessel was leased to LLNL by BMW AG and was shipped in a metallic container - see **Figure 8**. Main characteristics of the vessel are summarized on **Table 2**. A support system was then designed to accommodate neck support, on which the vessel was installed and wrapped with MLI before being installed in our 3 m^3 containment vessel – see **Figure 9**. Please note that the insulation provided in this set-up was estimated to be an order of magnitude (~100 Watts) larger than it would be for an on-board, carefully insulated system.

Table 2: Characteristic of prototype pressure vessel

Manufacturer	BMW AG
Design	Type 3: Aluminum liner, Carbo Fiber overwrap
Outer Diameter	35 cm
Total Length	2 m
Internal Volume	109 Liters
Rated Pressure	350 bar

Table 3: Description of the temperature sensors installed on the prototype pressure vessel

Name	Type	Location	Installed by
RTD A	Pt 111 sensor 9417.12 (serial P33382)	Inlet tube (on steel)	LLNL
RTD B	Pt 111 sensor 9417.01 (serial P33115)	Inlet tube (on steel)	LLNL
RTD C	Pt 100	Back of vessel (on Aluminum)	BMW
RTD D	Pt 100	Middle of vessel (on composite), top	BMW

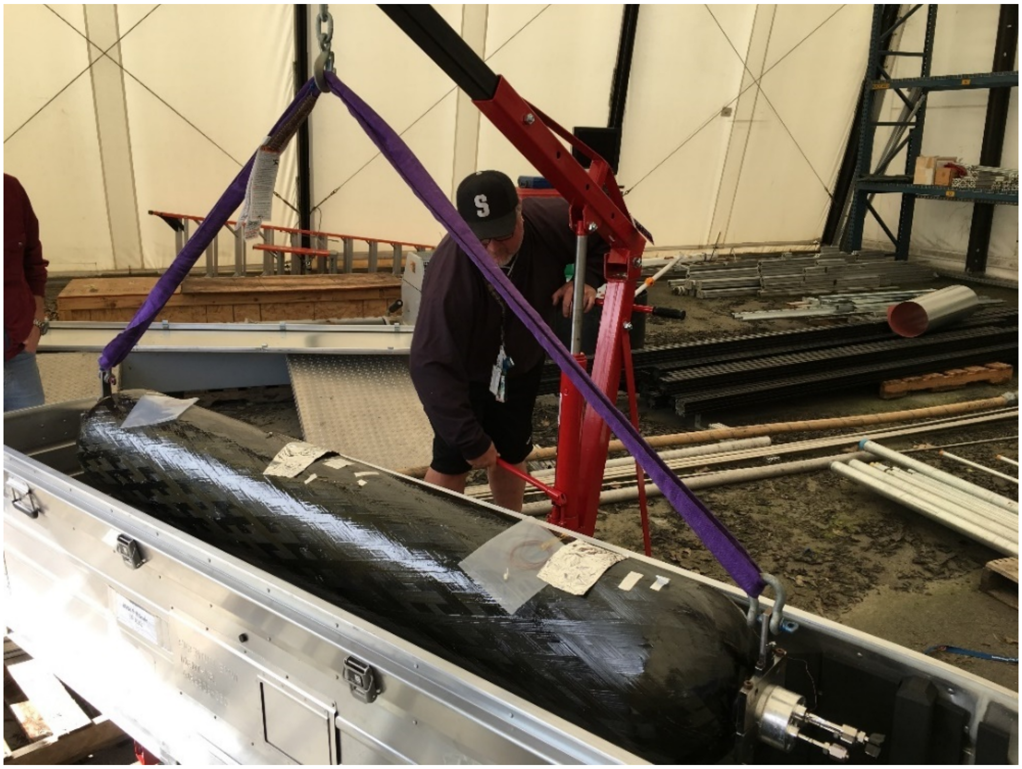


Figure 8: Prototype pressure vessel being extracted from shipping container

Figure 9: Prototype pressure vessel wrapped with ~10 layers of MLI, prior to being inserted into containment vessel

The prototype vessel was instrumented with 5 Resistance Temperature Detectors (RTD): 3 Pt 100 sensors provided and installed by BMW, and 2 additional Pt 111 sensors added by LLNL. The 3 Pt 100 sensors were located in the front (on the fill pipe), the middle (on the carbon fiber) and on the back. The front sensor exhibited mis-communication with the DAQ and was thus dis-regarded. The 2 Pt 111 installed by LLNL were collocated with the font Pt 100 sensor from BMW. At last, a Type K thermocouple was used to measured ambient temperature in the containment vessel.

Measuring accurately the temperature of the H_2 in the pressure vessel presents a few challenges. First, the temperature sensors have to be able to measure temperature over a wide range, from near 20 K to ambient. Second, the temperature is not necessarily uniform in space and in time, whether it is through the volume of H_2 or through the vessel's wall (Aluminum liner then carbon fiber), where the convection and conduction add delay in addition to the sensor's response time. Third, the adhesion between the temperature sensor and the surface it is supposed to measure the temperature of is often far from perfect, and extra time delays and reading error may occur. At last, the temperature sensor has to be robust, i.e. it must be capable of reading the temperature variations over a long period of time (weeks to months to years) with minimal loss in accuracy and precision, since the sensor is typically located in the vacuum space where calibration or sensor replacement is particularly demanding. For all the reasons mentioned above, temperature measurement is identified as one of the most important metrological challenges for cryogenic pressure vessel testing with H_2.

The pressure is measured using a 0-1,700 bar transducer manufacturer by TelTru (P143 model, part # P143A3L1AG11A630D3), located outside the containment vessel – see **Figure 6**, with a 0.25% FSO accuracy, i.e. 4.25 bar.

2. Cycling results

In this section we present an overview of the cycling in terms of LH_2 inventory, and pressure and temperature cycles experienced by the prototype pressure vessel.

2.1. LH_2 inventory

A total of 8 LH_2 deliveries were carried were carried out over the course of the testing period. Those deliveries are summarized in Table 4. The 3rd and 4th columns are data directly communicated by Linde, while the results from the 5th column have been shared with us by the driver (weighted mass of the trailer before and after delivery). That raw data from the 3rd and 4th columns is then used by Linde for billing. The last column is the adjusted delivered amount of LH_2, based on the fact that some amount of Diesel fuel is used during the trip between LLNL and the scale (estimated to be around 38 miles round trip, equivalent to 48 lbs, or 21 kg, or Diesel consumed). A total of **4,933 kg of LH_2** was billed to LLNL. However, not all the H_2 was used for cycling. For example, the 04/19/2017 delivery happened the day the LH_2 pump failed, thus the LH_2 delivered that day was not used for cycling. Additionally, there were some periods of boil-off between delivery and cycling (for example, the 01/16/2017 delivered LH_2 was not used for cycling until 04/04/2017), and therefore only an estimated **3,010 kg of LH_2** was effectively used for cycling the prototype vessel.

Table 4: Summary of LH_2 deliveries at LLNL

Date of Delivery	Trailer Number	Billed Amount (Gallons)	Billed Amount (SCF)	Billed Amount, from scale (kg)	Adjusted delivered Amount (kg)
01/16/2017	7016	2370	268,782	635	613
04/10/2017	7016	2133	241,904	571	550
04/19/2017	7009	2370	268,782	635	613
01/02/2018	7021	2099	238,080	562	541
02/08/2018	7028	2912	330,240	780	759
02/13/2018	7021	2099	238,080	562	541
02/20/2018	7021	2065	234,240	553	532
02/27/2018	7021	2370	268,782	633	612

The variations of the inventory and vapor pressure in the 3,300 gallon Dewar are shown on **Figure 10** for the entire testing period, in days since February 13th 2017. The amount of LH_2 is estimated based on the measured level of LH_2 (in inH_2O) that is converted in gallons based on the calibration report (see Appendix A), then converted in mass assuming a density of 63.5 g/L. This density was estimated using a 2-phase thermodynamic model previously built by LLNL. The 7 deliveries (all except the 01/16/2017 delivery) are shown on the figure and illustrated by a vertical blue line. We can see that virtually all the 04/19/2017 LH_2 delivery was "wasted" through boil-off only (not cycling), and that it took a little over 4.5 months (135 days) to empty completely by heat transfer with the environment alone. The set pressure of the relief device is 30 psig (3 bar absolute). We can see that the vapor pressure in the Dewar plummets when the inventory is near 0 (see days 210 to 320, and again after day 425), due to the small inventory after a long time. Interestingly, it is worth noting that the Dewar was still "somewhat" cold for the next LH_2 delivery on 01/04/2018, i.e. almost 9 months after the previous delivery, as inferred by the driver who did not experience any difficulties filling the vessel.

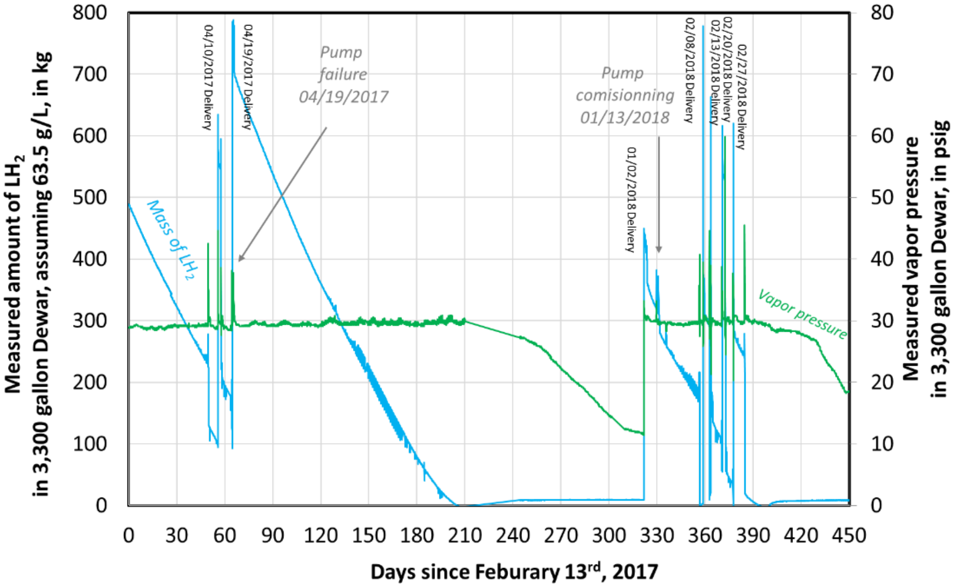


Figure 10: Amount of LH_2 (blue, left axis) and vapor pressure (green, right axis) in 3,300 gallon Dewar over the testing period

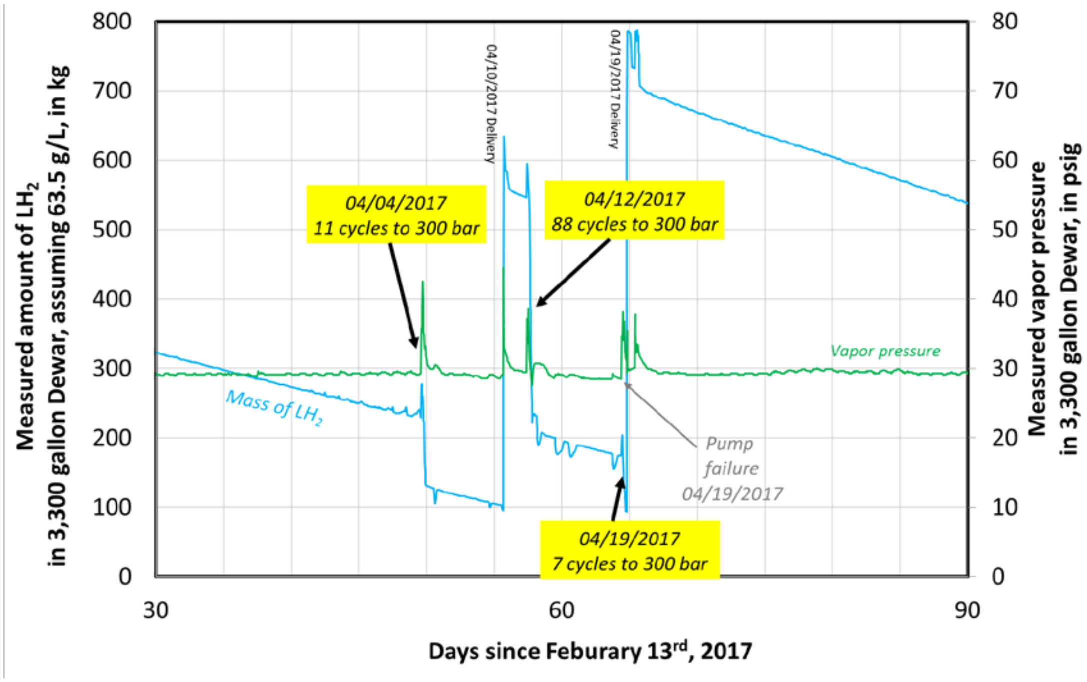


Figure 11: Zoom-in of **Figure 10** for the April 2017 timeframe, including vessel cycling to 300 bar, in yellow

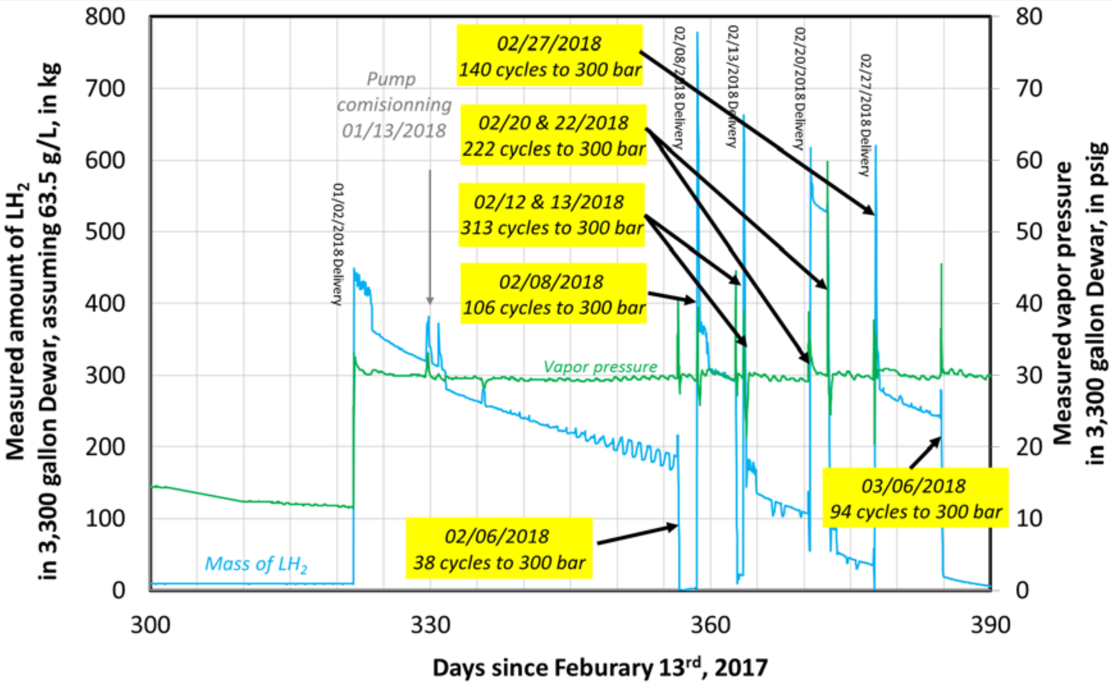


Figure 12: Zoom-in of **Figure 10** for the January through March 2018 timeframe, including vessel cycling to 300 bar, in yellow

2.2. Overview of the pressure cycling of the prototype vessel

The prototype vessel was cycled to 300 bar using the LH$_2$ pump over 11 non-consecutive days, ranging from 7 to 200 cycles per day, between April 4th 2017 and March 6th 2018. Those cycles are summarized on **Table 5.** Cycling was interrupted on April 19th 2017 when the LH$_2$ pump experienced a failure, and was resumed on February 6th 2018 with a repaired system. Most of the cycles with the LH$_2$ pump were carried out from 50 to 300 bar in order to maximize the number of cycles per day. In between cycling days, the pressure vessel was left to warm up and underwent vents to keep the pressure below the rated pressure (350 bar). 1019 cycles to 300 bar were carried out with the LH$_2$ pump, and an extra 18 pressure cycles (including 11 to 350 bar) were performed by warm-up only; for a total of 1,037 pressure cycles above 300 bar.

Table 5: Summary of the cycling of the prototype vessel to 300 bar using the LH_2 pump. Pressure values are reported with a +/-5 bar tolerance

Cycling #	Cycling Date	Number of Pressure Cycles to 300 bar using the LH_2 pump	Minimum Pressure before Fill with LH_2 pump	Additional pressure cycling above 300 bar by warm-up alone
1	04/04/2017	11	2 bar	1 to 350 bar
2	04/12/2017	88	2 bar (8 cycles) 50 bar (80 cycles)	3 to 300 bar 1 to 350 bar
3	04/19/2017	7	2 bar (1 cycle) 50 bar (6 cycles)	1 to 300 bar
4	02/06/2018	38	Ambient (1 cycle) 10 bar (37 cycles)	3 to 350 bar 1 to 330 bar
5	02/08/2018	106	10 bar (16 cycles) 20 bar (10 cycles) 30 bar (10 cycles) 40 bar (10 cycles) 50 bar (60 cycles)	3 to 350 bar 1 to 320 bar 1 to 310 bar
6	02/12/2018	113	50 bar	
7	02/13/2018	200	50 bar	
8	02/20/2018	22	50 bar	
9	02/22/2018	200	Ambient (2 cycles) 50 bar (198 cycles)	1 to 350 bar
10	02/27/2018	140	75 bar (1 cycles) 50 bar (139 cycles)	
11	03/06/2018	94	50 bar	2 to 350 bar

Table 6: Constant pressure parking. Pressure values are reported with a +/- 5 bar tolerance

Period	Number of days	Pressure
04/07/17 to 04/12/2017	5	245 to 260 bar
04/14/2017 to 04/19/2017	5	295 to 300 bar
04/20/2017 to 07/07/2017	77	250 to 285 bar
02/16 to 02/20/2018	4	200 to 220 bar
02/23 to 02/27/2018	4	75 bar
02/23 to 02/27/2018	5	180 bar
Since 03/08/2018	180+ (on-going)	350 bar

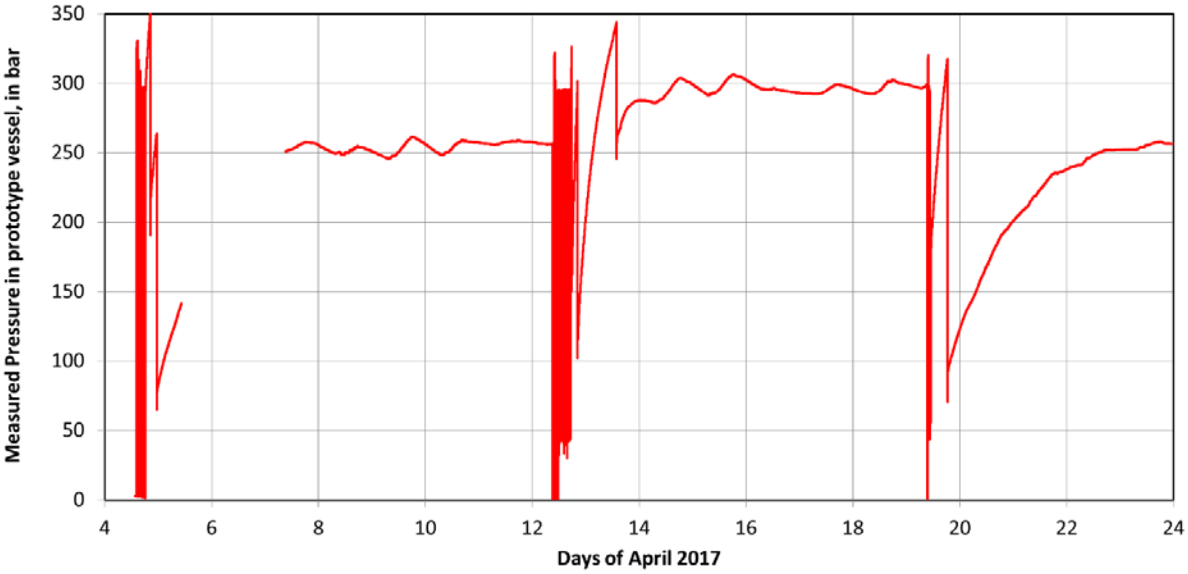


Figure 13: Measured pressure in prototype vessel during the month of April 2017. 3 cycling days: April 4th, 12th and 19th

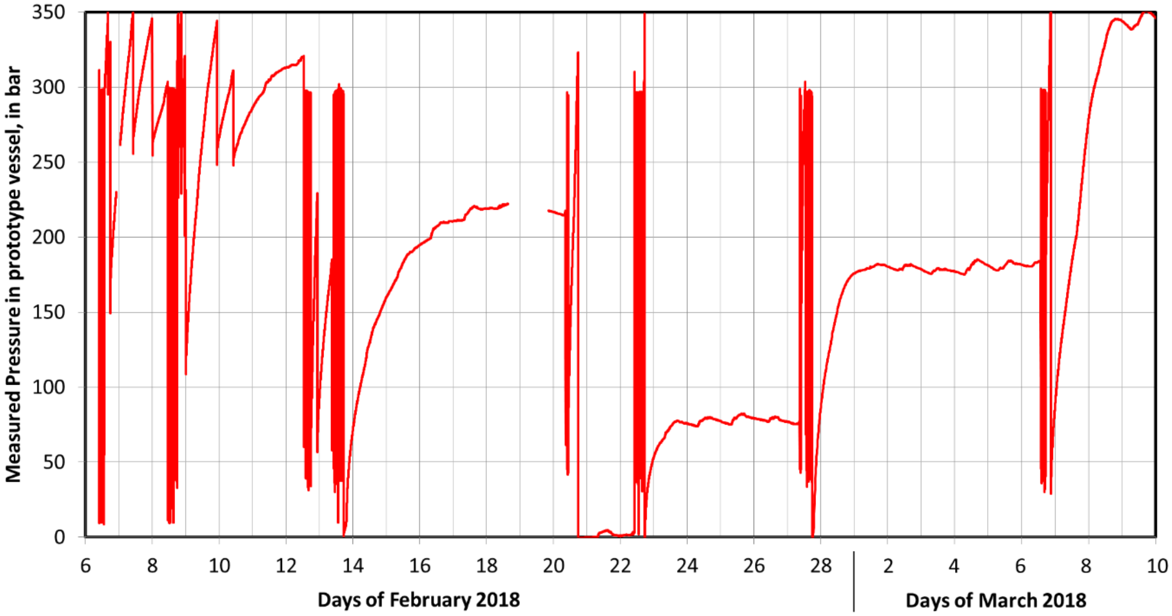


Figure 14: Measured pressure in prototype vessel during the month of February and March 2018. 8 cycling days: February 6th, 8th, 12th, 13th, 20th, 22nd and 27th, and March 6th.

2.3. Measuring temperatures and H_2 densities

In order to illustrate the challenges with measuring temperatures, and hence inferring the H_2 density using the pressure, we present experimental results measured on our test bench during the cycling time-frame. **Figure 15** shows the variations of pressure and temperature (left axis) as well as the inferred densities for each RTD (right axis) measured on April 12th and 13th 2017. The RTDs were installed in March 2017, and 11 cryogenic cycles were performed on April 4th 2017, prior to the 88 cycles shown here. The vessel is thus assumed to be at uniform temperature at the beginning of the day, since it has soaked at ambient temperature for more than a week.

The thick lines refer to each temperature sensor (RTD A, B, C and D, and type K thermocouple), while the thin lines represent the inferred H_2 densities computed from the pressure (red line) and for each of the measured temperatures with RTD A through D (four values). RTD A and B measured almost identical values, therefore their corresponding lines are difficult to tell apart on the figure.

Before cycling began around 10 AM on April 12th, the vessel was kept at near ambient temperature at a pressure of 258 bar, hence an estimated density of 18 g/L. We can see that the temperatures measured by the RTDs are all within a few degrees of each other (RTD A, B and C are virtually identical, while RTD C is about 2.5 K lower), and are similar with the values recorded by the type K thermocouple (grey line). This relative relationship of the 5 temperature sensors seems to be maintained after the cycling is over and the pressure vessel is back to near ambient temperature (end of the day on April 13th), thus we assume that the cryogenic cycling has not deteriorated the sensors.

Figure 16 shows the same data as **Figure 15** between 8 AM and noon of April 12th, 2017. The pressure vessel is first vented to near ambient pressure (from 258 bar, around 9:15 AM), undergoing a cooling from ~290 to 270 K due to H_2 expansion. The vessel is then filled 4 times using the LH_2 pump, gradually reducing the temperatures from ~270 K to as low as 50 K. During pressure cycling with the LH_2 pump, we can see that RTD A and B follow each other pretty well and measure lowest temperature, while RTD C and D seem to experience a lag, presumably overestimating the temperature. After 8 cycles between near ambient pressure and 300 bar, 80 consecutive fills between 50 and 300 bar are carried out, exhibiting repeatable temperature variations patterns - see **Figure 17**. **Figure 18** shows a zoomed-in version of the previous figures, between 3 and 3:15 PM on April 12th, 2017. About 4 pressure cycles to 300 bar are carried out over that timeframe, with fill times less than 2 minutes, hold time less than 1 minutes and venting time less than 20 seconds. The measured vessel temperatures are between 60 K and 100 K. The estimated H_2 densities keep varying over the 1-minute hold time, which means that time window is not sufficient to infer accurately the actual H_2 temperature. As a result, we decided to achieve a longer hold time at the end for the 88 cycles, by holding the pressure at the end of the last cycle – see **Figure 19**, where the last 3 pressure cycles of the day are shown. It takes about 0.15 hr, or 10 minutes for the inferred densities from RTD A and B to stabilize, at around 57 g/L (assuming RTD A and B are the most accurate temperature sensors). Going back to **Figure 15**, the four RTDs agree again only at temperatures around 230 / 240 K (before 13.5 days).

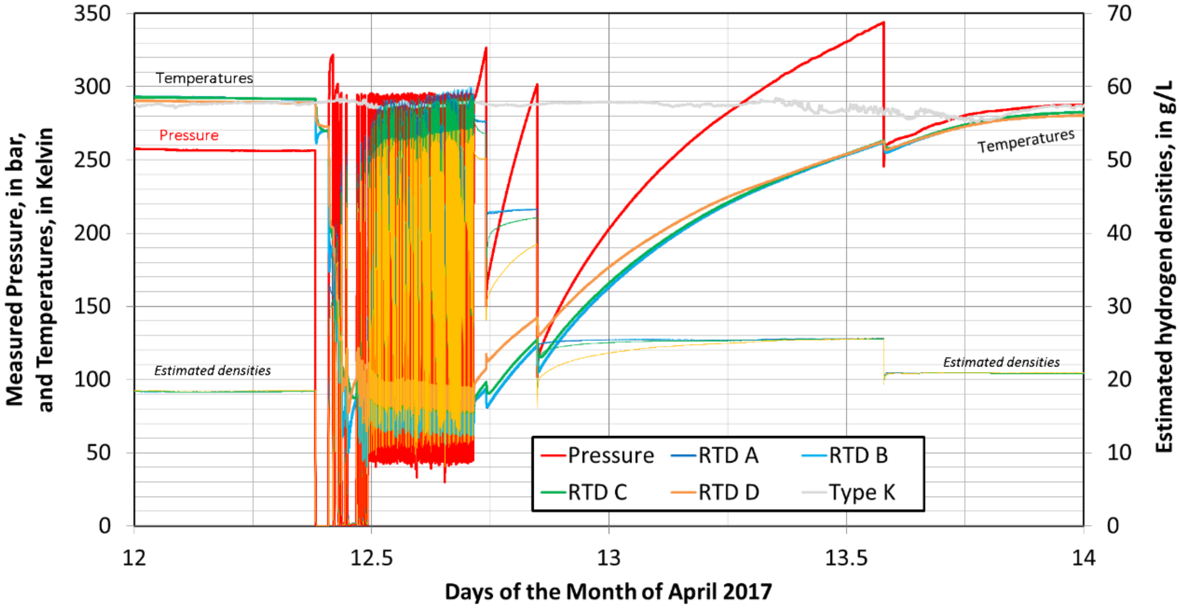


Figure 15: Temperature and pressure variations (left axis) and estimated H_2 densities (thin lines, right axis) measured on April 12th and 13th, 2017.

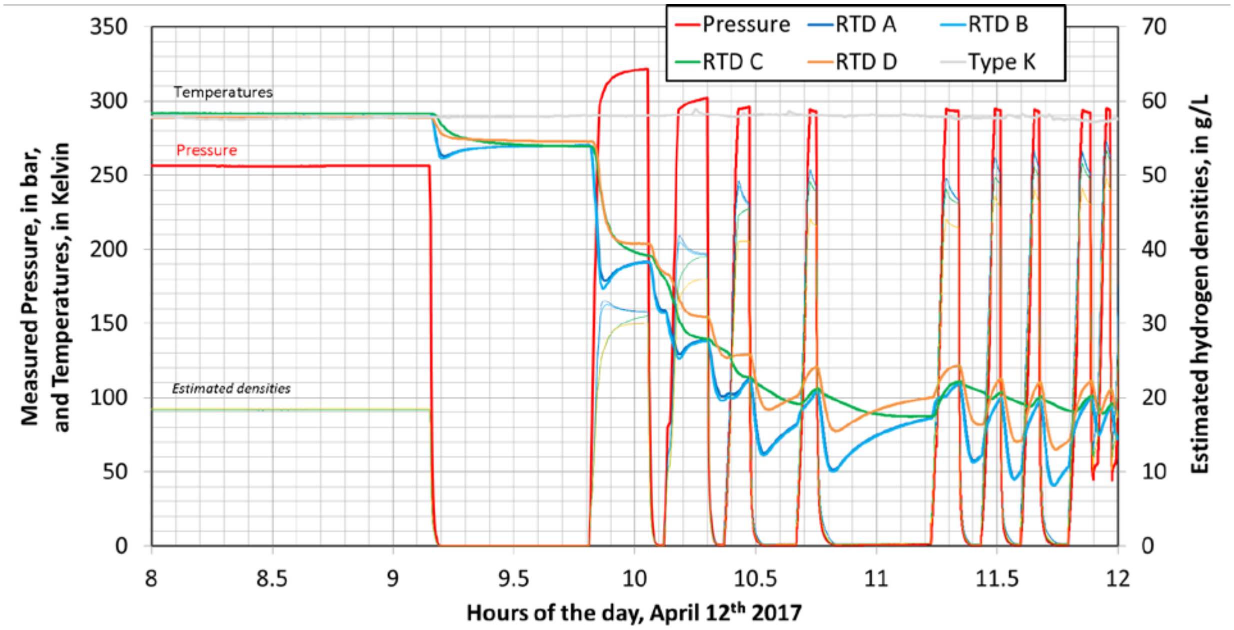


Figure 16: Temperature and pressure variations (left axis) and estimated H_2 densities (thin lines, right axis) measured between 8 AM and noon on April 12th, 2017.

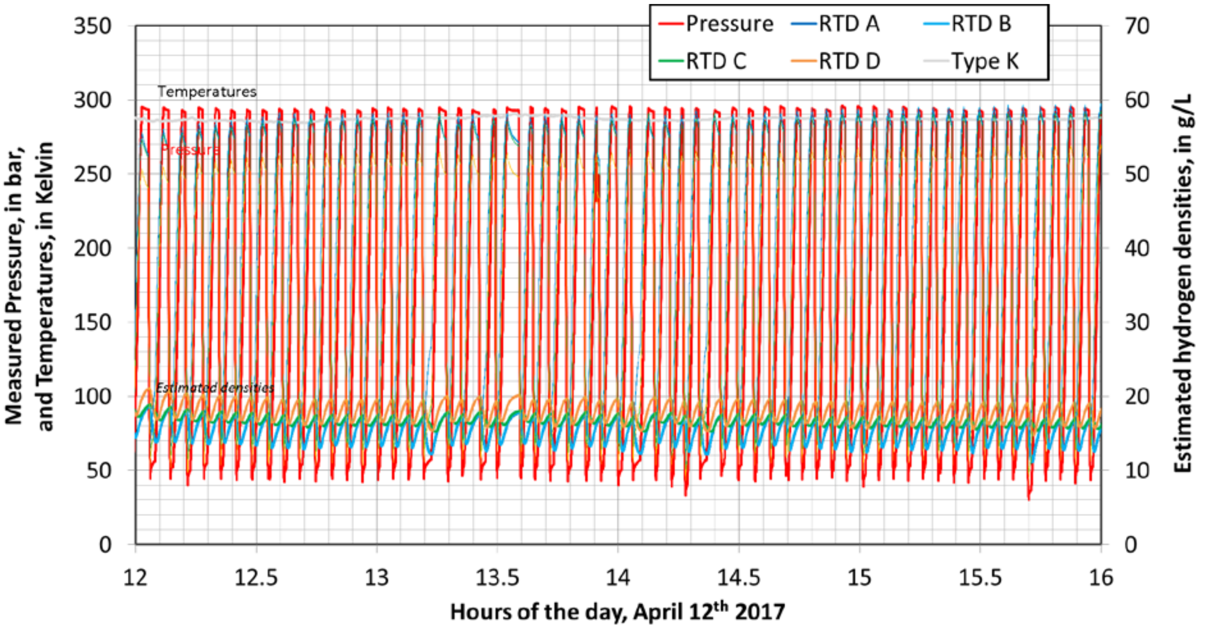


Figure 17: Temperature and pressure variations (left axis) and estimated H_2 densities (thin lines, right axis) measured between noon and 4 PM on April 12th, 2017.

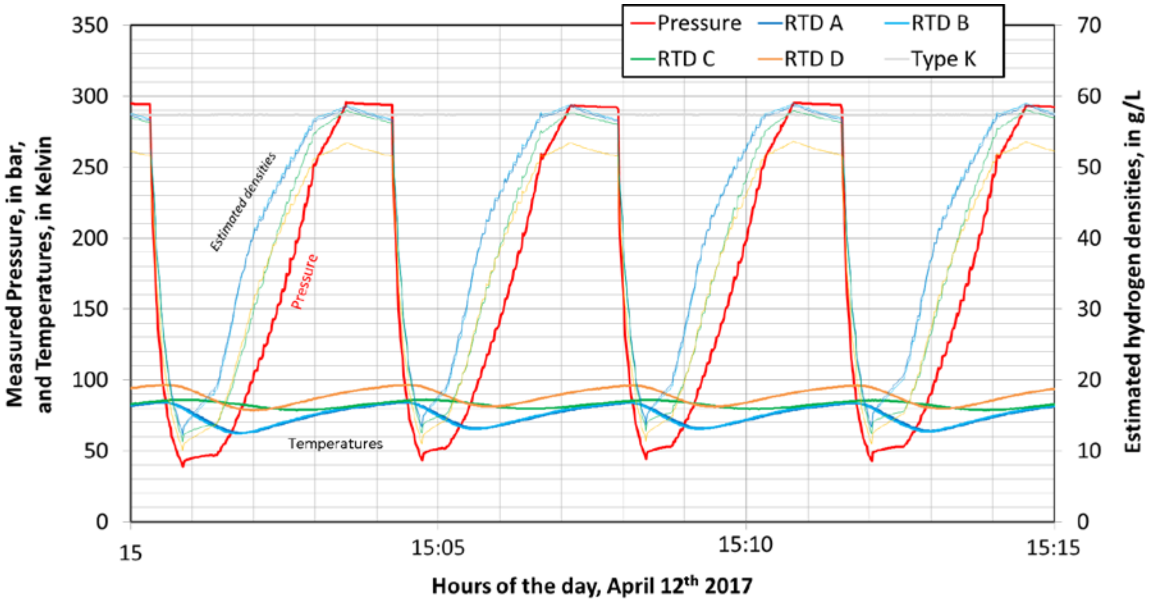


Figure 18: Temperature and pressure variations (left axis) and estimated H_2 densities (thin lines, right axis) measured between 3 PM and 3:15 PM on April 12th, 2017.

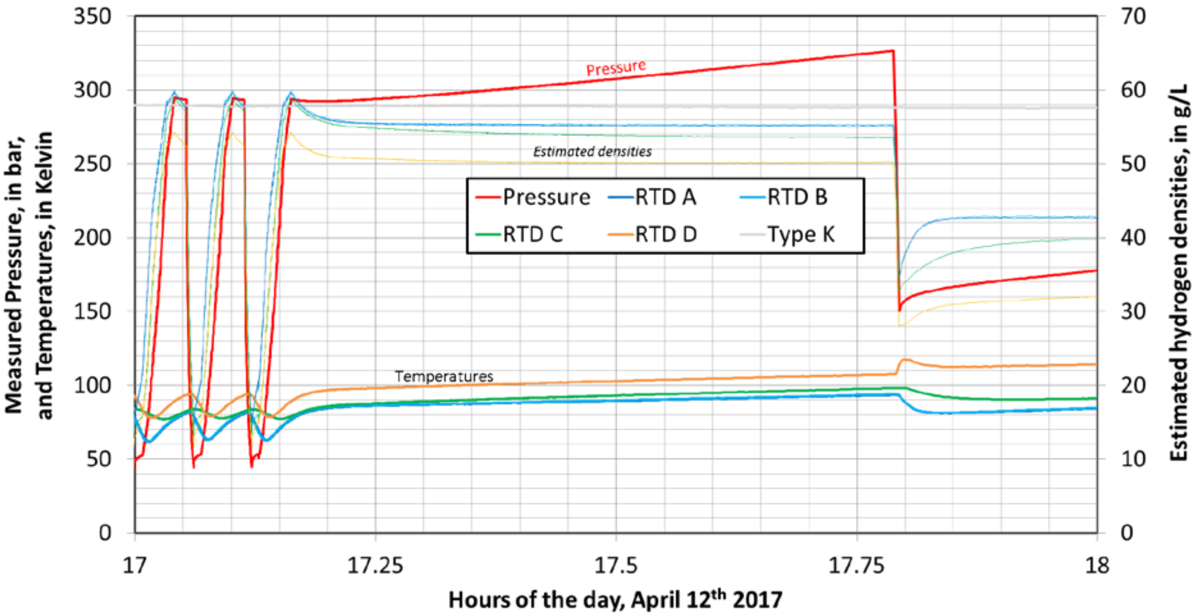


Figure 19: Temperature and pressure variations (left axis) and estimated H_2 densities (thin lines, right axis) measured between 5 PM and 6 PM on April 12th, 2017.

2.4. Description of the 11 cycling days

Cycling #1: 04/04/2017

See

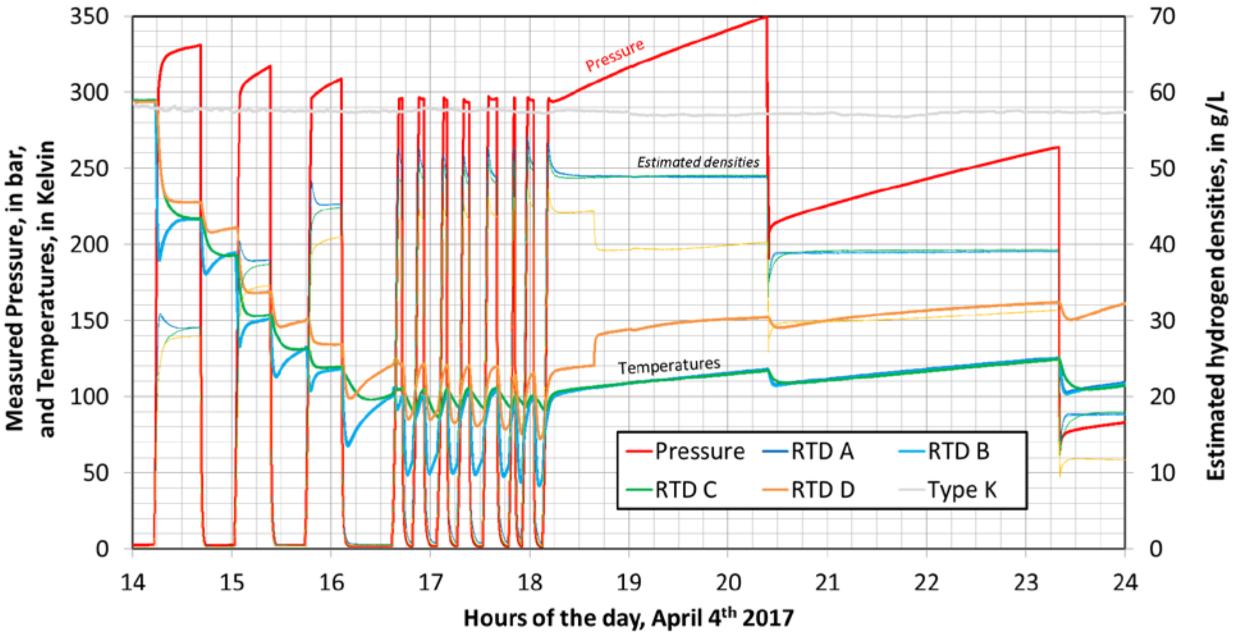


Figure 20. Cycling #1 represents the first cycling of the pressure vessel to 300 bar. The prototype vessel was initially at ambient temperatures (See RTD A, B, C and D) and ambient pressure. The first 3 cycles were performed between ambient pressure and 300 bar, and the vessel was kept close for 20 to 30 minutes after the fill to 300 bar in order to allow the temperatures to equilibrate, inferred by constant densities from RTD A and B. As such, the first 3 fills between ambient pressure and 300 bar reached estimated H_2 densities of 29 g/L, 38 and 45 g/L, respectively. The next 4 fills were performed almost back-to-back (no equilibration of the temperatures), reaching an estimated final H_2 density of 49 g/L – observed through a self-pressurization between 300 bar and 350 bar. Note that RTD D exhibited an expected behavior past ~ 6:40 PM, which was observed again in following cycles.

The vessel was then vented twice (at 8:30 PM and 11:15 PM) to reach an estimated H_2 density of 18 g/L, that was maintained until next cycling.

Cycling #2: 04/12/2017

See

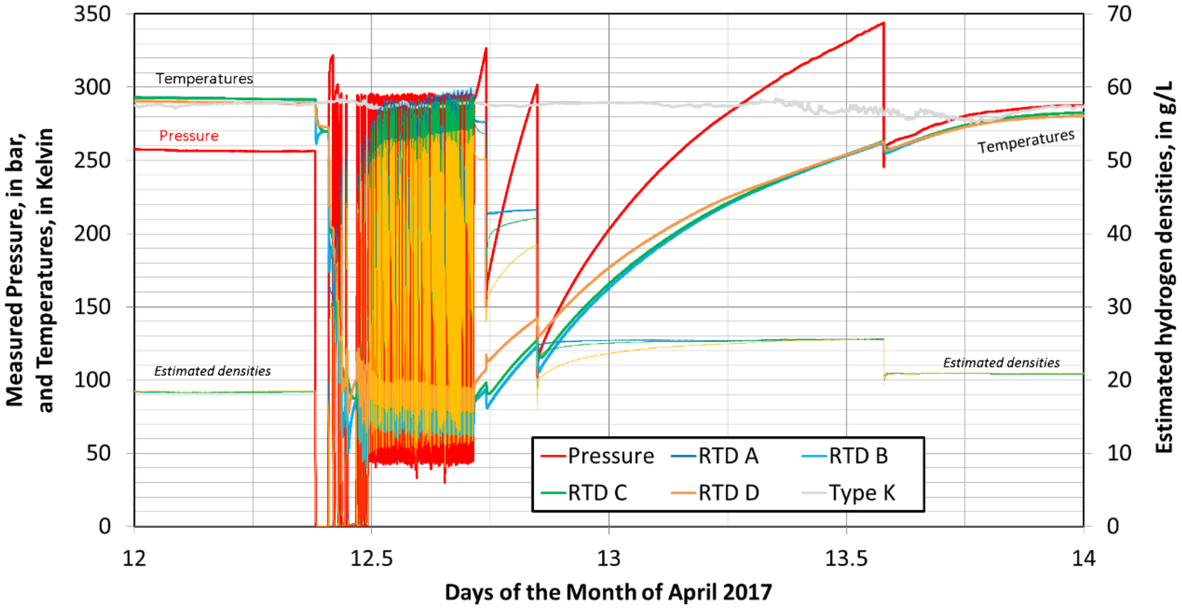
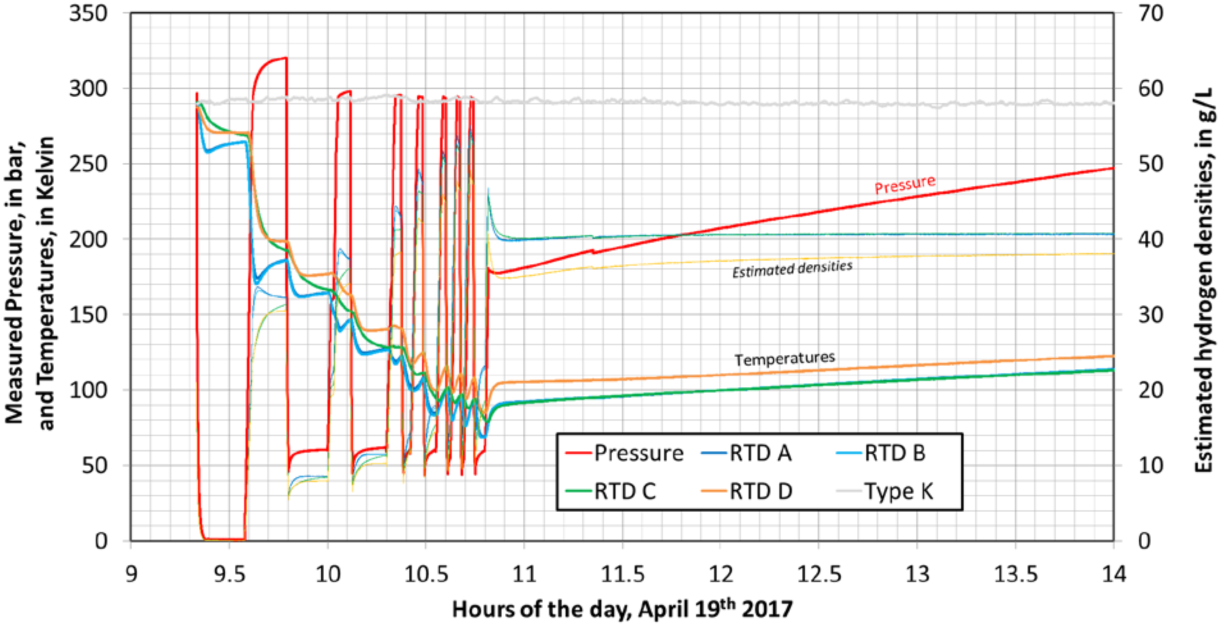


Figure 15 through **Figure 19**. Prior to cycling #2, the prototype vessel was kept at constant pressure (~258 bar) and ambient temperature for almost a week. The temperature sensors all indicated similar values at ambient conditions. The vessel was vented to almost atmospheric pressure (2 bar reading) then filled 8 times to 300 bar, then vented to 50 bar and filled 80 times to 300 bar. At the end of the last fill to 30 bar, the vessel was not vented in order to try to reach uniform temperatures. 4 consecutive vents were then performed so that the vessel reached ambient temperature on the afternoon of the next day (April 13th), with an indicated H_2 density of 21 g/L.

<u>Cycling #3: 04/19/2017</u>

See **Figure 21** through



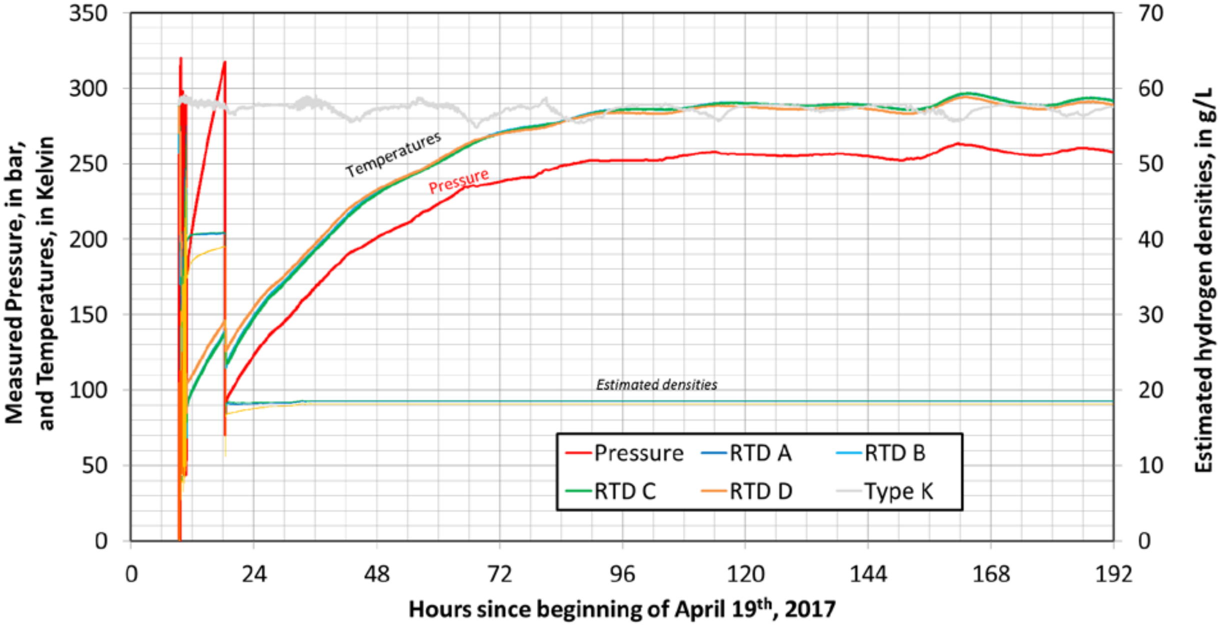


Figure 23. The vessel was first vented from near 300 bar to near atmospheric pressure, then filled 7 times to 300 bar (once from 2 bar, 6 times from 50 bar). On the 8th fill of the day, the pump could not pressurize past 180 bar. Subsequent testing indicated that the pump was malfunctioning and thus needed to be sent back to Germany, thus prematurely ending the cycling for 2017.

Cycling #4: 02/06/2018

See

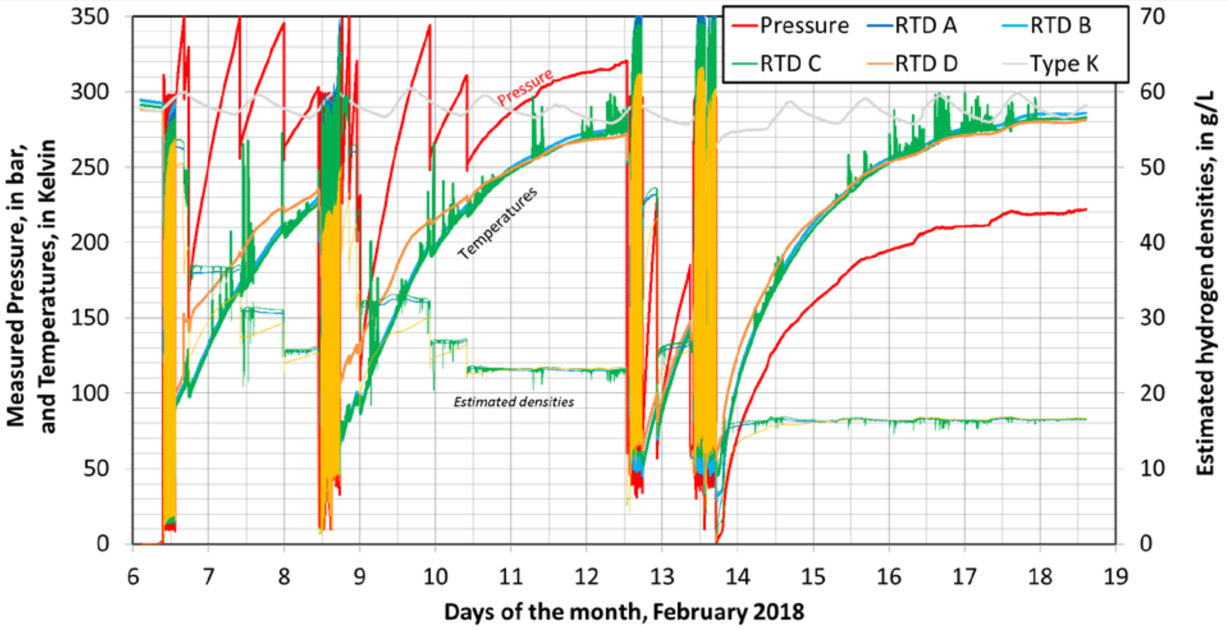


Figure 24 through **Figure 26.** Cycling #4 is the first cycling with the repaired pump. Temperature data indicate that the 5 sensors still measured consistently the temperature (all near ambient values prior to cycling). The vessel is initially at near ambient pressure. After the initial fill from ambient to 300 bar, the vessel was filled 37 times between 10 and 300 bar, and was not vented after the last fill in order to infer uniform temperature. RTD A and RTD B exhibited again fairly identical behavior, which led us to assume that the sensors did not experience any noticeable degradation since the last time cycling was performed, i.e. about 9.5 months earlier. It is also worth noting that some noise was observed for the first time on the signal from RTD C, that was then seen for the rest of the cycling.

The vessel reached 350 bar 2 hour after the fill to 300 bar, reaching a temperature of 105 K thus an estimated H_2 density of 53 g/L. Based on the variation of internal energy (720-606 =114 kJ/kg), an estimated 91 Watts of heat transfer was experienced by the H_2 at those conditions (between 93 and 105 K), assuming an inner volume of 109 Liters. The vessel then underwent 4 vents (3 from 350 bar, 1 from 330 bar) and was at 300 bar with 26 g/L of H_2 prior to the next cycling on 02/08/2018.

Cycling #5: 02/08/2018

See **Figure 27** and **Figure 28.** The vessel was first vented from 300 to 10 bar, then underwent fills to 300 bar from various initial pressures using the following sequence: 11 fills from 10 bar, 5 fills from 20 bar, 5 fills from 30 bar, 5 fills rom 40 bar, 5 fills from 50 bar, 5 fills from 40 bar, 5 fills from 30 bar, 5 fills from 20 bar, and 5 fills from 10 bar. The remaining cycles were then all carried out between 50 and 300 bar. The pressure vessel was kept at constant pressure after the last fill in order to infer uniform temperature. The vessel then underwent 5 vents (3 from 350 bar, 1 from 320 bar, 1 from 310 bar) and was at 320 bar and (estimated H_2 density: 23 g/L) on the morning of the next cycling day, on April 12th, 2018.

Cycling #6: 02/12/2018

See **Figure 29** and **Figure 30**. The vessel was first vented from 320 bar to 60 bar. At the end of cycling #6, the vessel was vented to 50 bar and maintained at those conditions, in order to reach uniform temperature and estimate initial H_2 density when filling from 50 bar. RTD A, B and C all converge toward similar temperatures within approximately 20 minutes, to an estimated H_2 density of 46 g/L.

Cycling #7: 02/13/2018

See **Figure 29** through **Figure 33**. The heater was used for the first time between 1:40 and 2 PM on 02/13/2018. Even though increasing temperatures could be observed, the heater had to be stopped since a leak occurred on one of the valves. Nevertheless, it was concluded that the heater was working as expected. At the end of cycling #7, the prototype vessel was completely vented to atmospheric pressure in order to reach to lowest temperature.

Cycling #8: 02/20/2018

See **Figure 34**. The vessel was first vented from ambient temperature, 218 bar to 60 bar, then underwent 22 pressure cycles to 300 bar. The last fill was vented from 300 to 50 bar, and left to warm-up, reaching a density of 44 g/L (indicated by RTD A, B and C) in about 5 hours. The vessel was then vented from 320 bar to near atmospheric pressure.

Cycling #9: 02/22/2018

See **Figure 35** and **Figure 36**. The vessel was first filled from atmospheric pressure and temperature to 300 bar, then underwent many cycles between 50 and 300 bar. Another attempt to use the heater was performed around 1:30 PM. The leak at the valve was still there, preventing us from filling the vessel using the heater. The last fill was kept close above 300 bar (exhibiting a max density of 66 g/L, consistent with values previously recorded), then vented from 350 bar to atmospheric pressure. The vessel then spent around 4 days at ambient temperature and 75 bar, i.e. an estimated H_2 density of 6 g/L.

Cycling #10: 02/27/2018

See **Figure 37** and **Figure 38**. On the morning of the 27th, the vessel ws first filled from 75 bar to 300 bar, then underwent cycling between 50 and 300 bar, until the pump could not keep its vessel full (around 0.7

inH$_2$O and 31.7 psig indicated on 3,300 gallon Dewar). The last fill was thus stopped at 120 bar, and the vessel was left to pressurize during the time the 3,300 gallon Dewar was refilled, indicating a density of 47 g/L. Cycling was resumed at around 1:15 PM, yet again between 50 and 300 bar. The last fill of the day was then vented from 300 bar to atmospheric pressure. Here again, similar to Cycling #7, the hydrogen reached the 2-phase region, indicated by an inflexion point in the temperature and pressure data. An estimated H$_2$ density of 14 g/L was reached. The vessel then spent 5 days at ambient temperature and 180 bar.

Cycling #11: 03/06/2018

See **Figure 39**. 94 cycles were performed between 50 and 300 bar, in addition to 2 pressure cycles to 150 bar and the last one to 165 bar, that was kept at pressure (estimated density: 58.5 g/L) and went from 165 to 350 bar in about 4 hours, thus about 122.5 Watts going into the hydrogen between 56 and 90 K. At last the vessel was vented from 350 bar ato 40 bar, in order to reach a density of around 23 g/L so that the vessel can be kept at maximum pressure (350 bar) for a long dormancy test. The vessel has been at 350 bar and ambient temperature since mid-day on March 8th, and is still at those conditions at the time this report is being written.

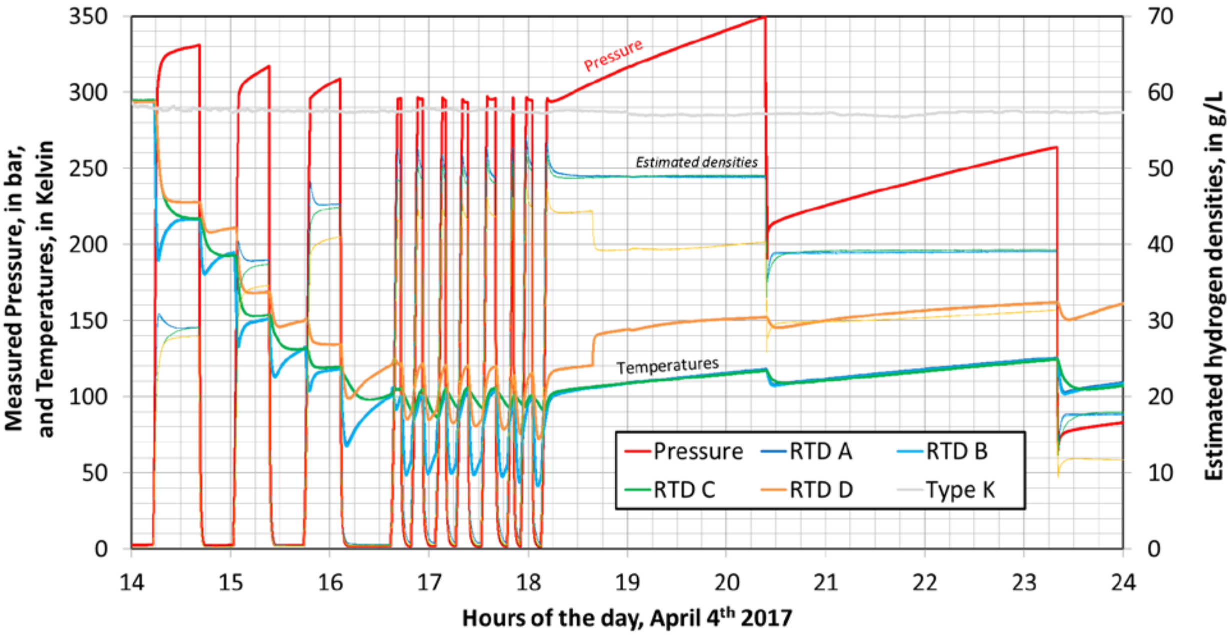


Figure 20: Pressure, temperature and estimated densities during the day of April 4th 2017 (Cycling #1)

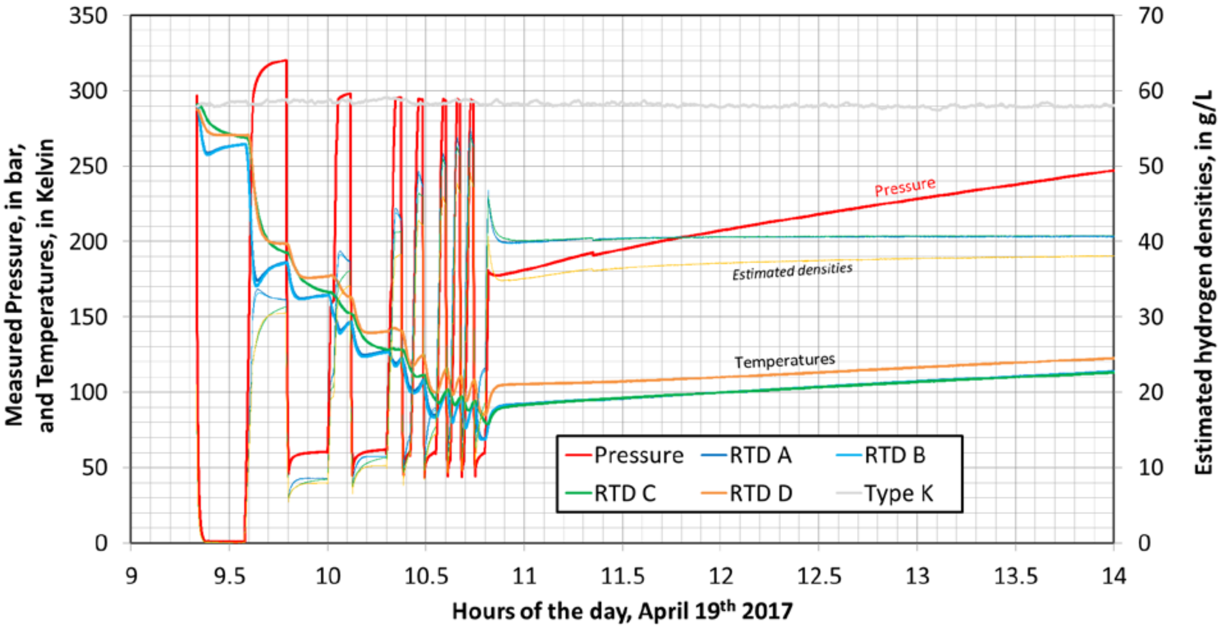


Figure 21: Pressure, temperature and estimated densities during the day of April 19th 2017 (Cycling #3)

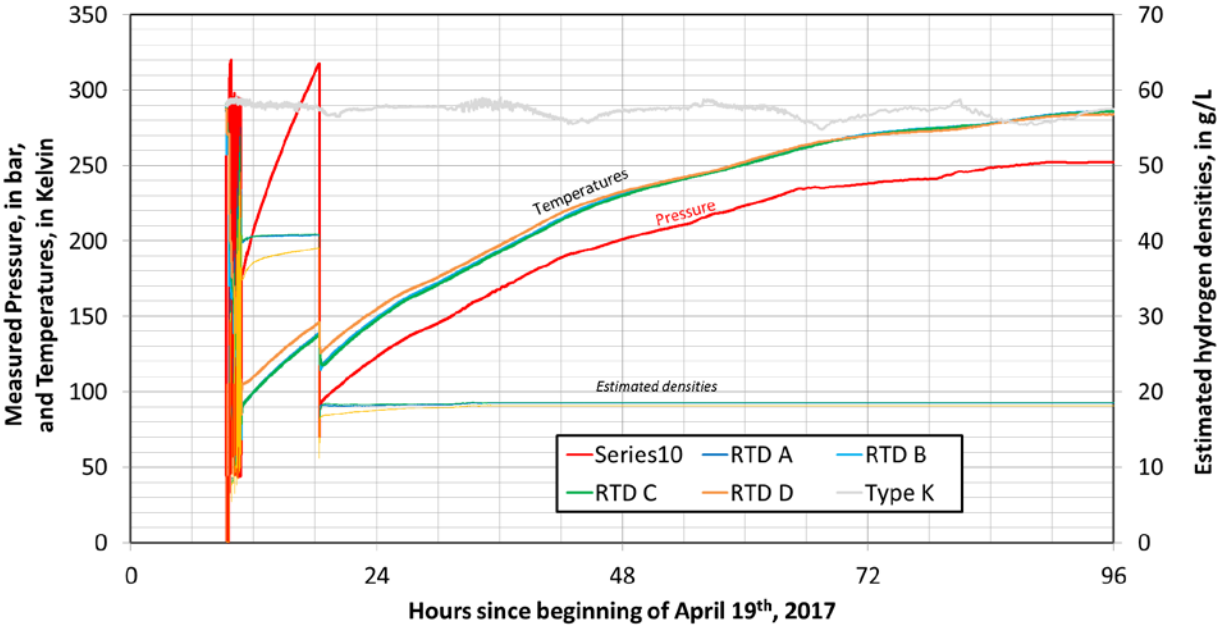


Figure 22: Pressure, temperature and estimated densities from April 19th to April 22nd 2017 (Cycling #3)

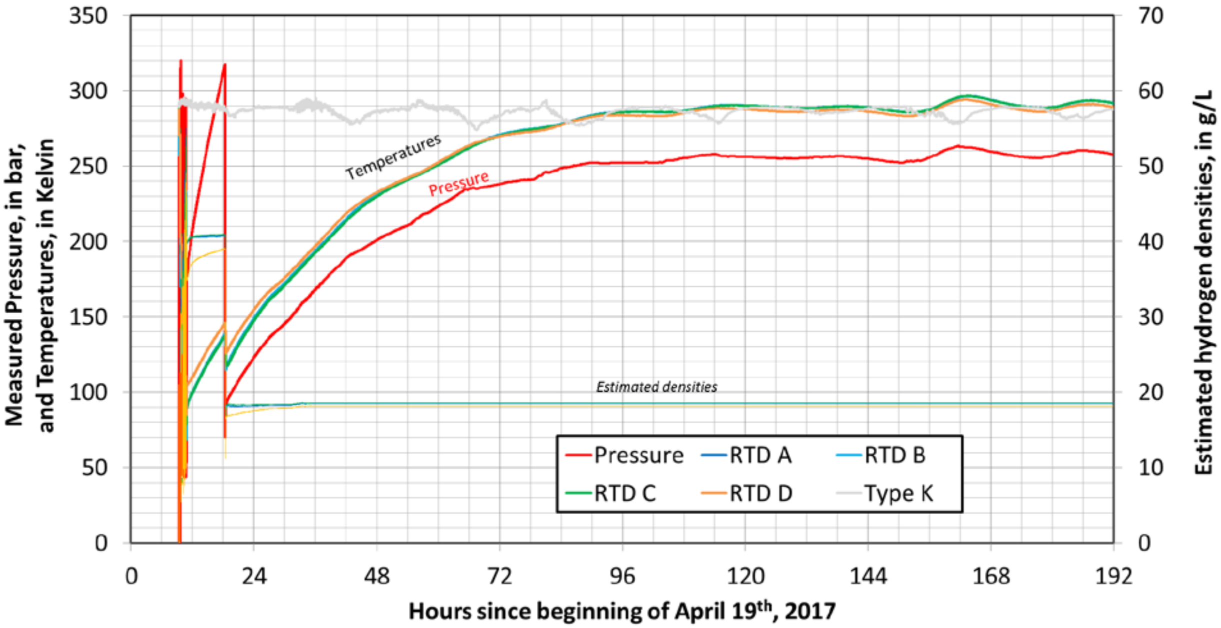


Figure 23: Pressure, temperature and estimated densities from April 19th to April 26th 2017 (Cycling #3)

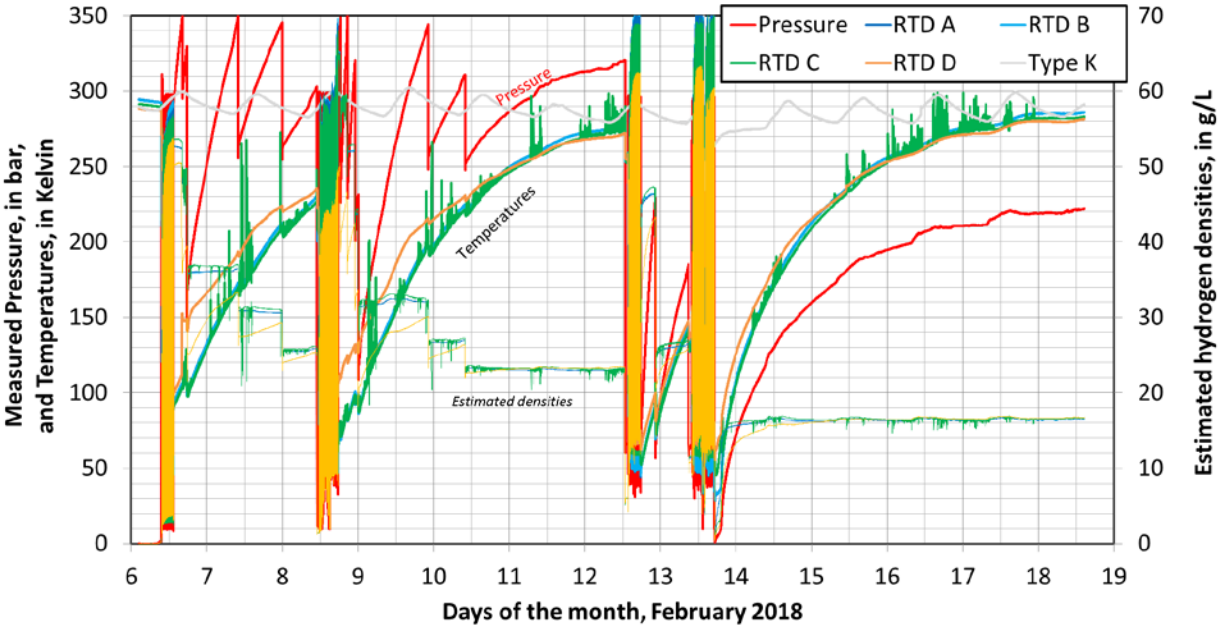


Figure 24: Pressure, temperature and estimated densities from February 6th to 19th 2018 (Cyclings #4 to 7)

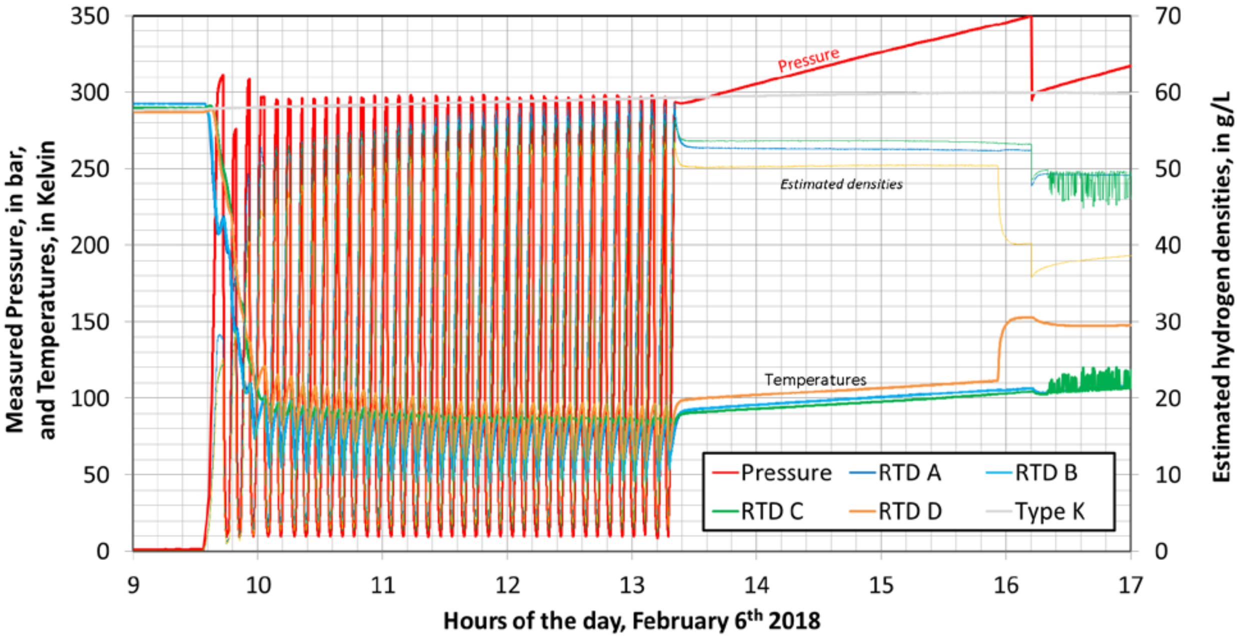


Figure 25: Pressure, temperature and estimated densities on February 6th 2018 (Cycling #4)

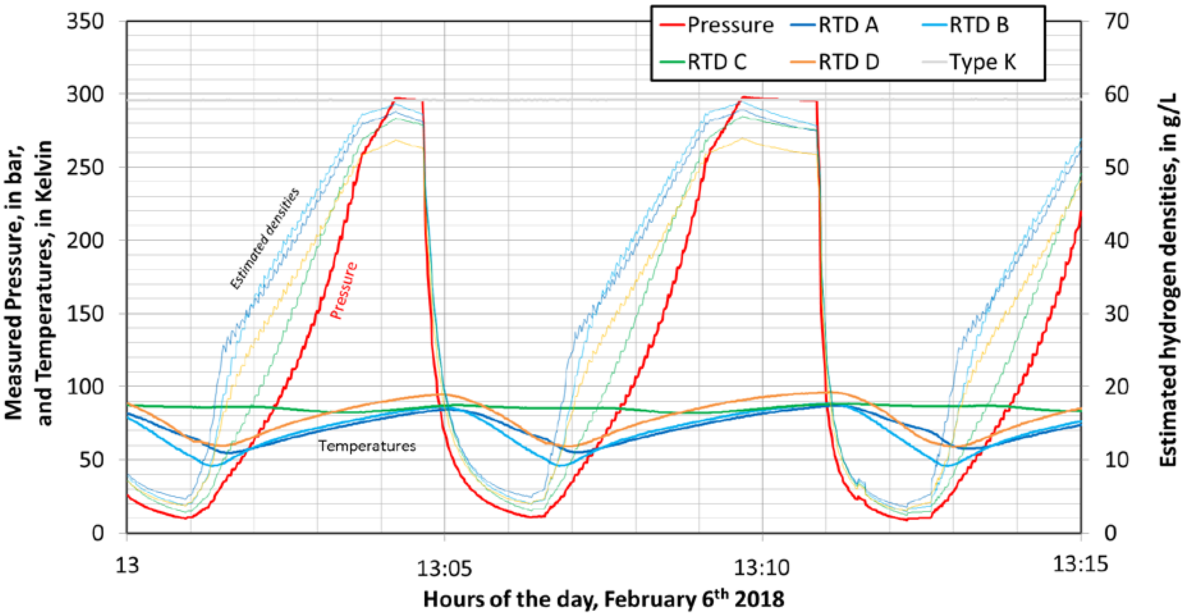


Figure 26: Pressure, temperature and estimated densities on February 6th 2018 (Cycling #4), details

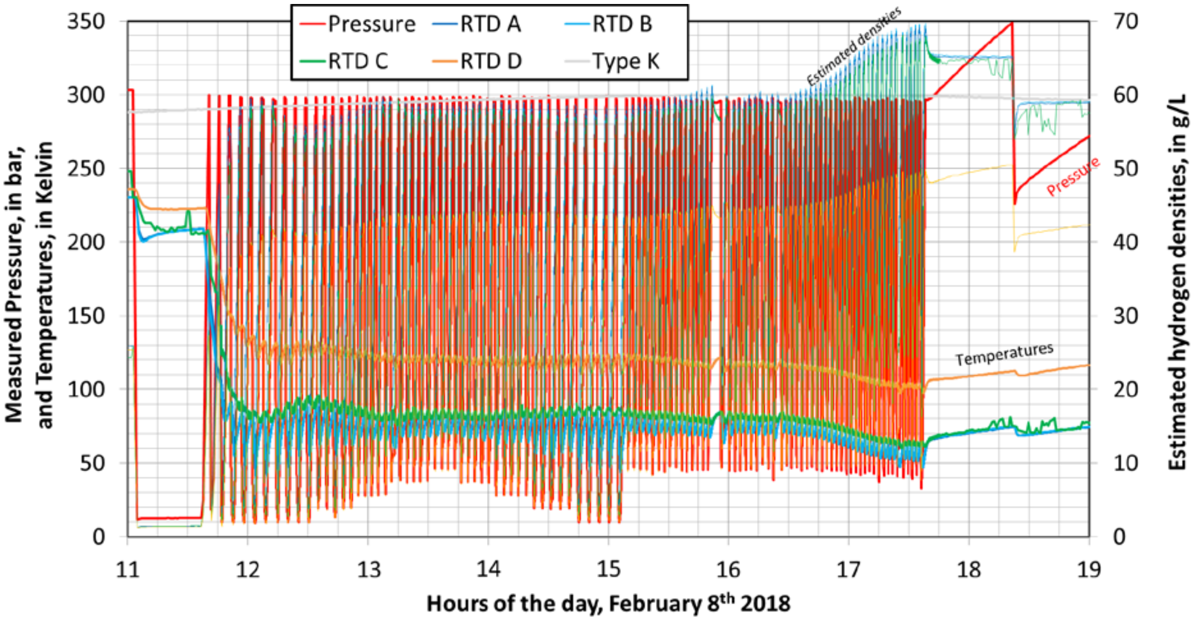


Figure 27: Pressure, temperature and estimated densities on February 8th 2018 (Cycling #5)

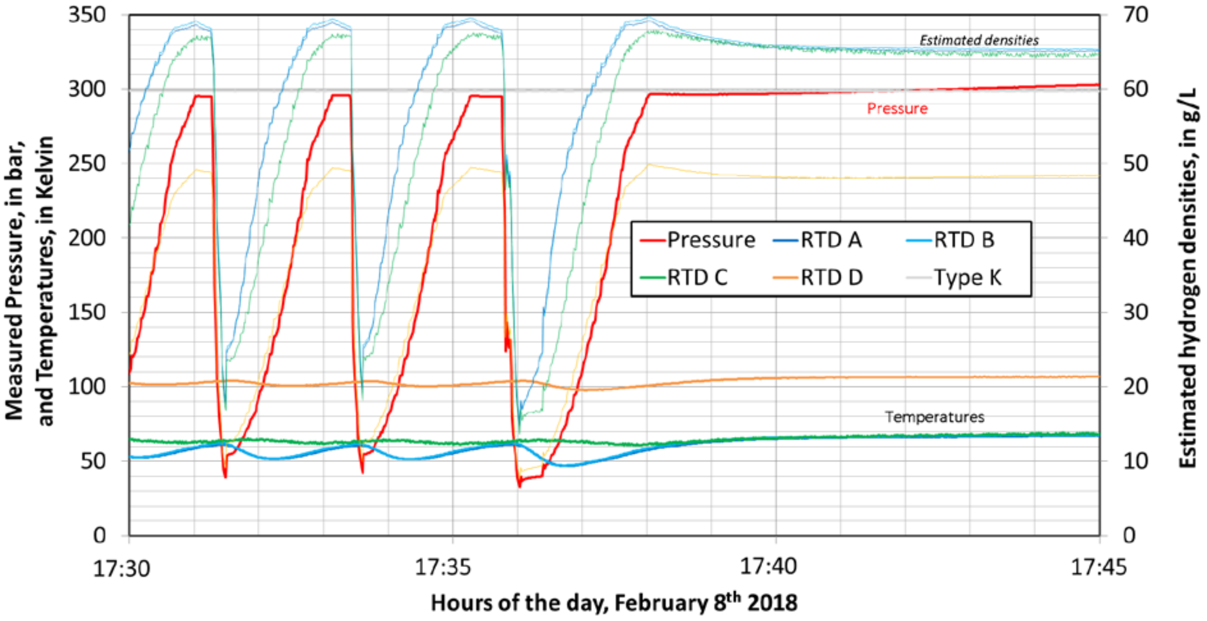


Figure 28: Pressure, temperature and estimated densities on February 8th 2018 (Cycling #5), details

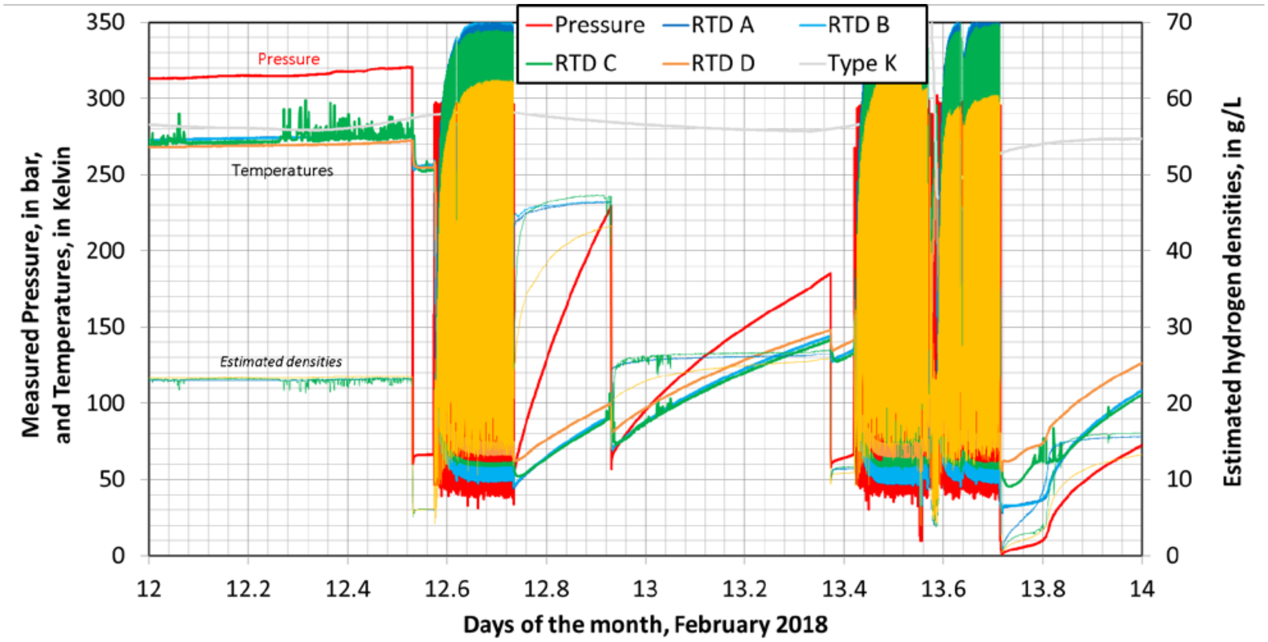


Figure 29: Pressure, temperature and estimated densities on February 12th and 13th 2018 (Cyclings #6 and #7)

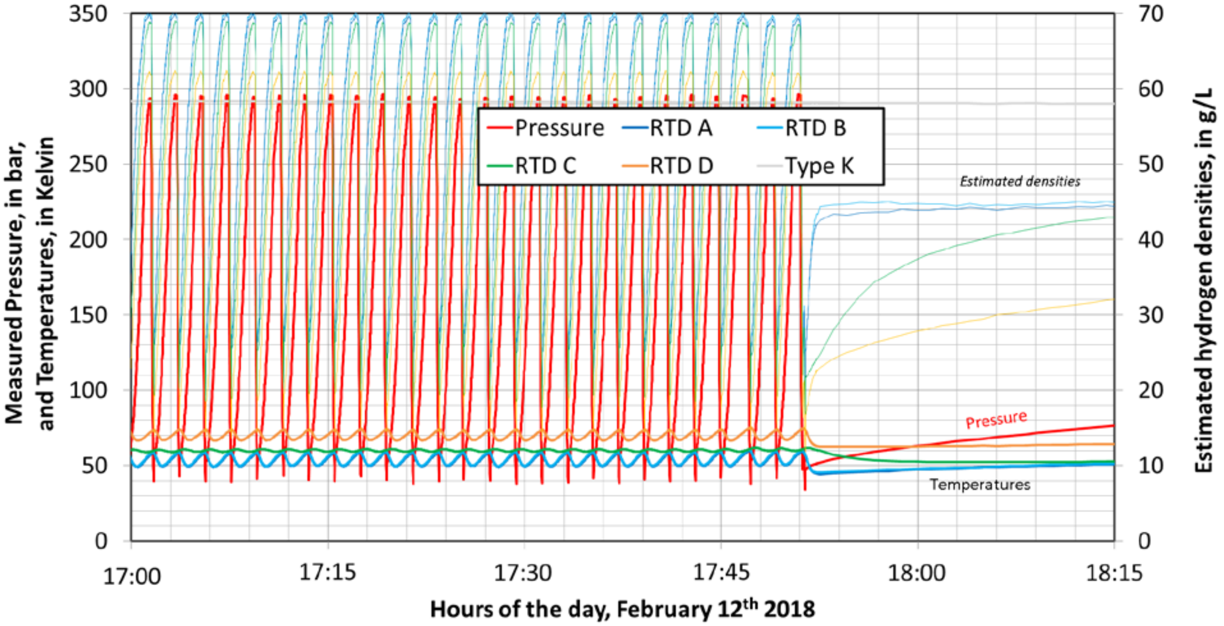


Figure 30: Pressure, temperature and estimated densities on February 12th 2018 (Cycling #6), details

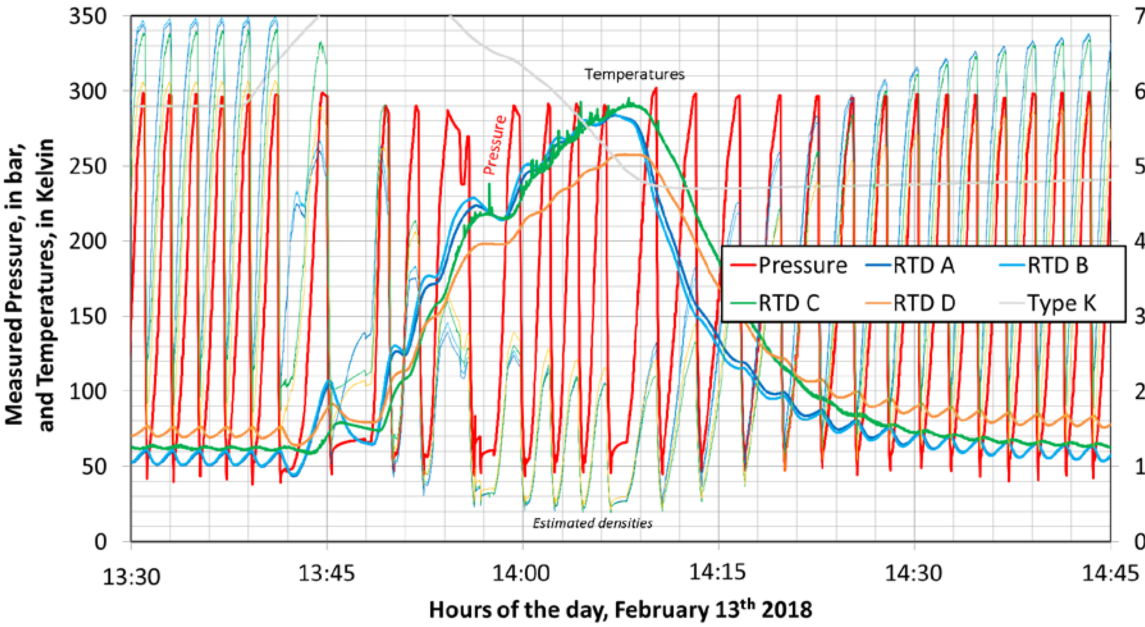


Figure 31: Pressure, temperature and estimated densities on February 13th 2018 (Cycling #7), details

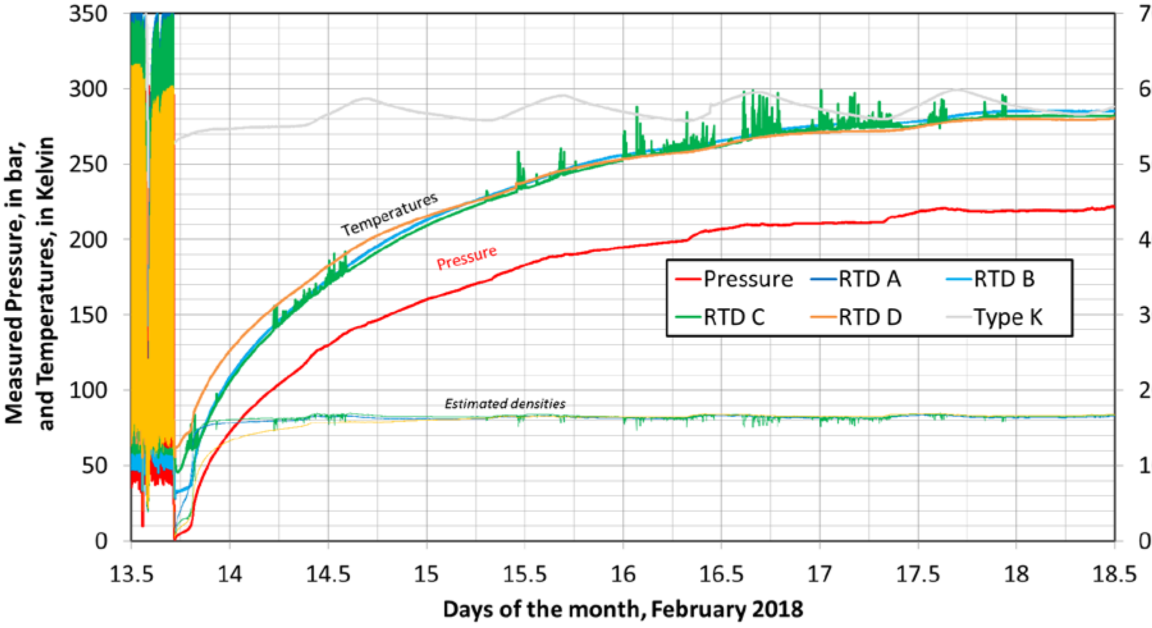


Figure 32: Pressure, temperature and estimated densities between February 13th and 19th 2018 (Cycling #7)

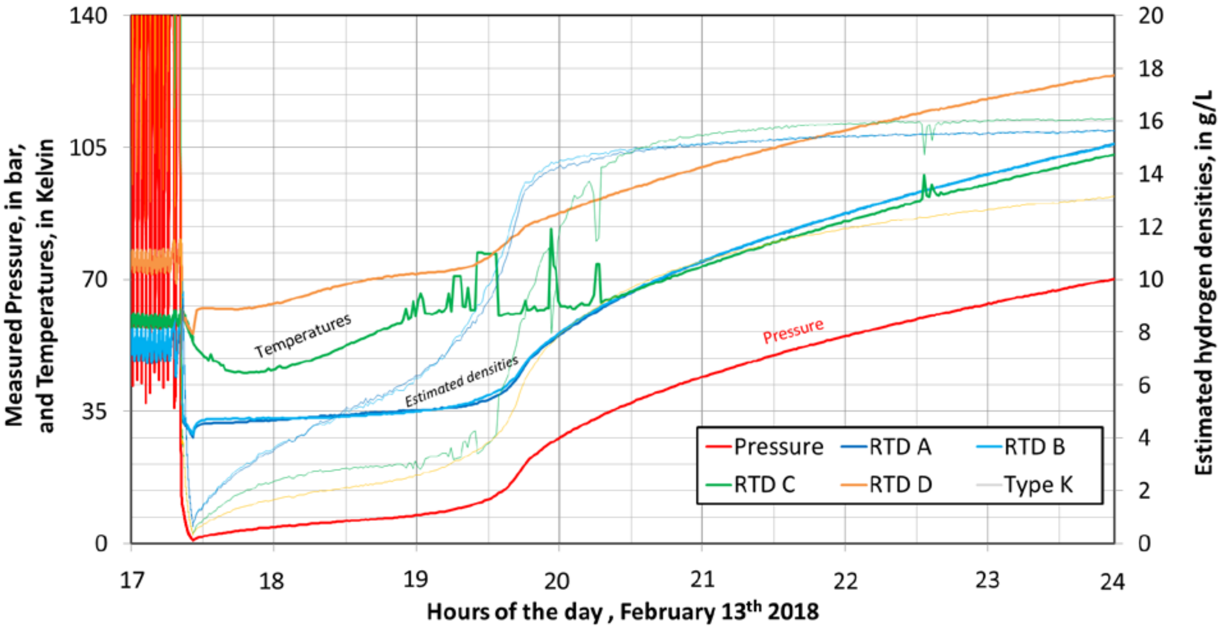


Figure 33: Pressure, temperature and estimated densities on February 13th 2018 (Cycling #7), details

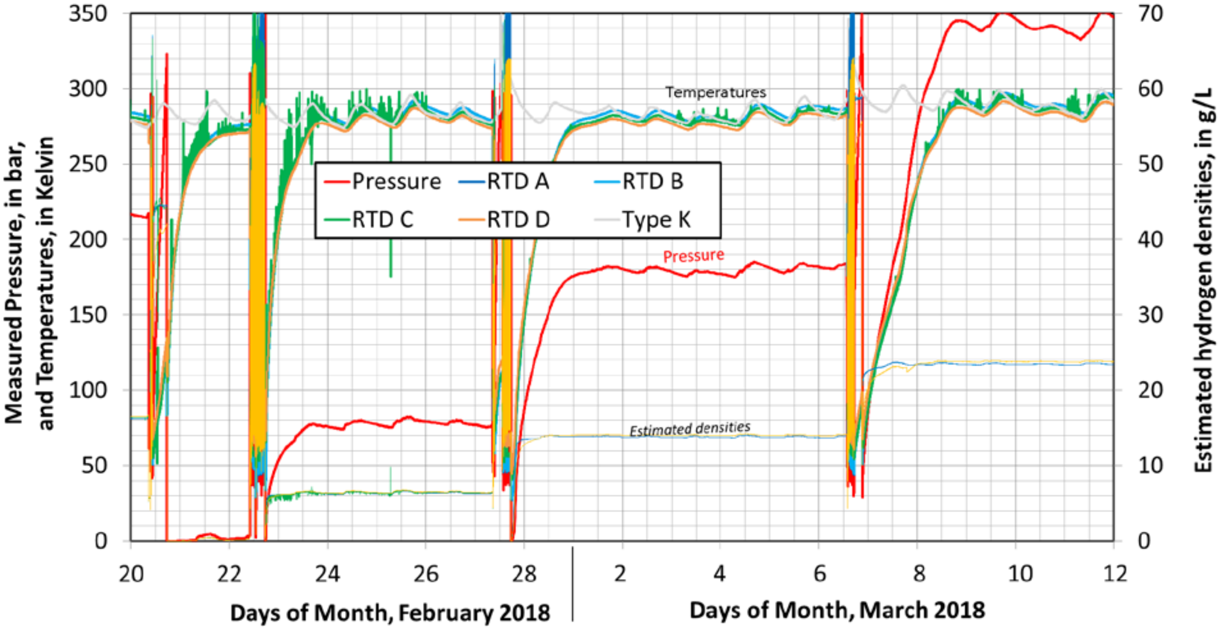


Figure 34: Pressure, temperature and estimated densities between February 20th and March 12th 2018 (Cycling #8 to 11)

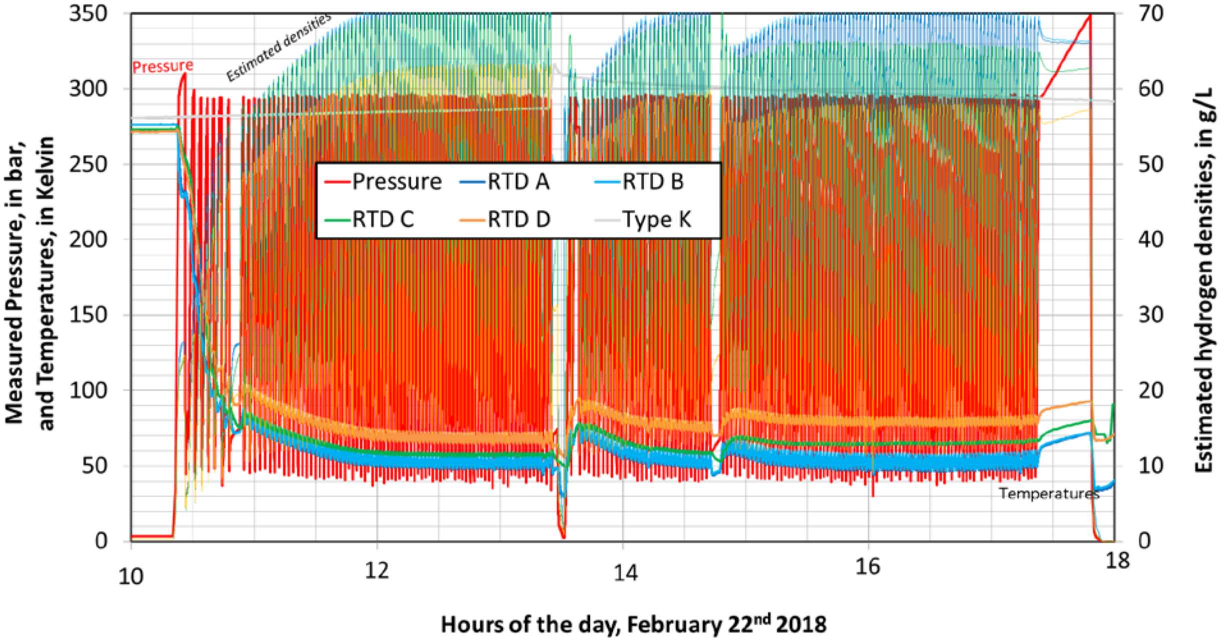


Figure 35: Pressure, temperature and estimated densities on February 22nd 2018 (Cycling #9)

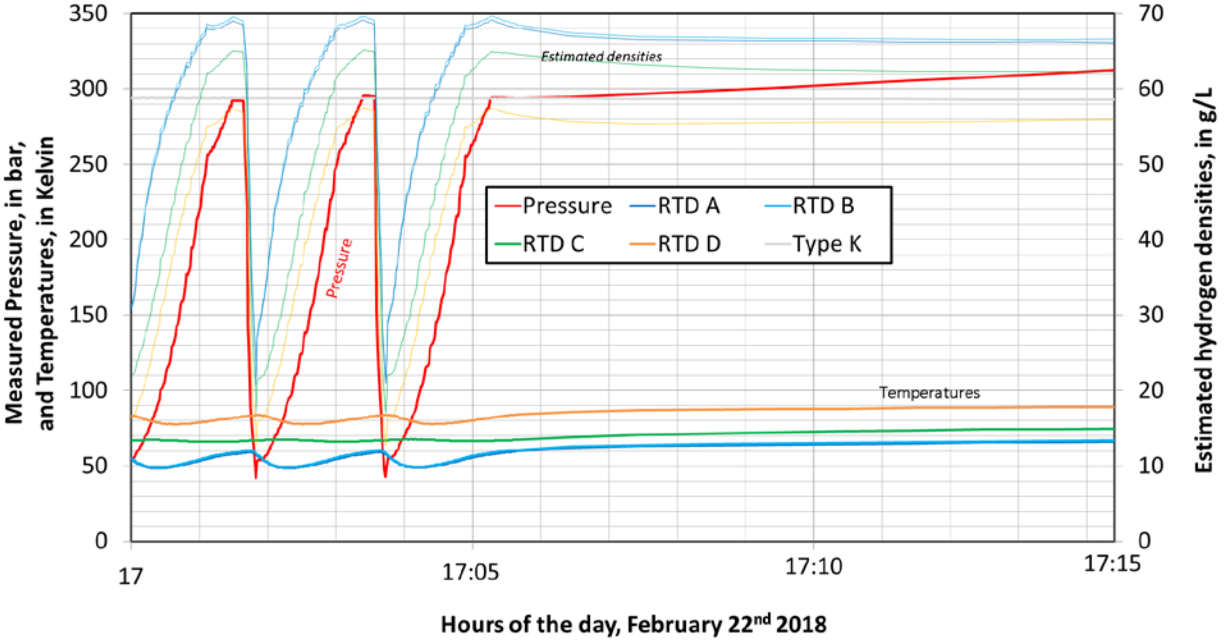


Figure 36: Pressure, temperature and estimated densities on February 22nd 2018 (Cycling #9), details

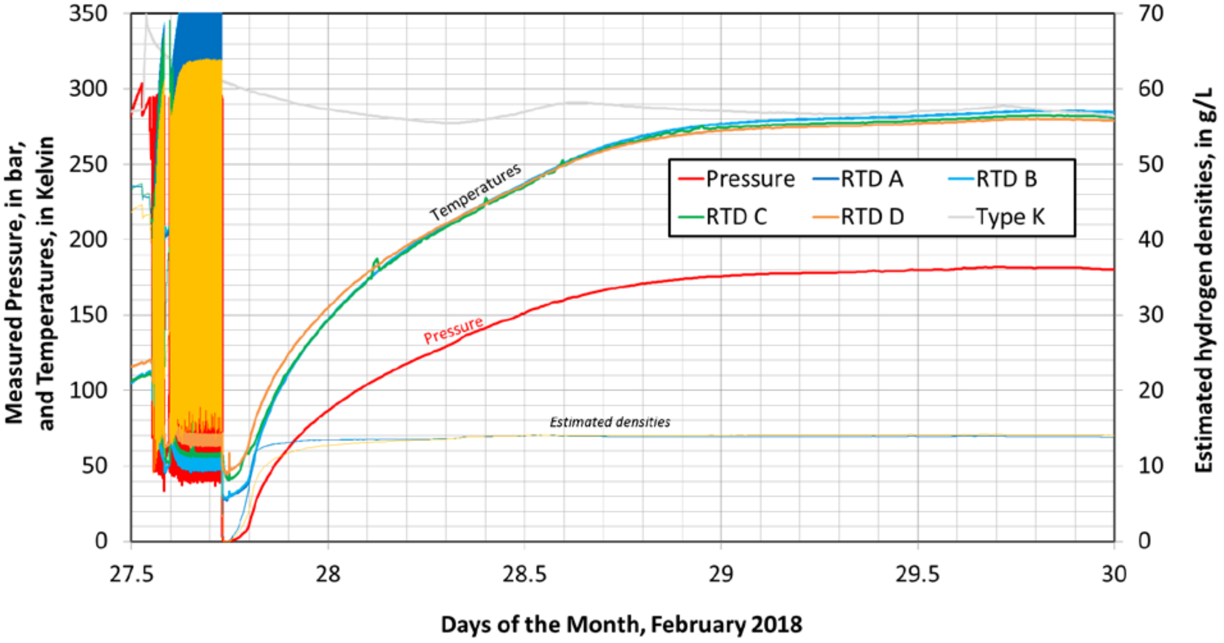


Figure 37: Pressure, temperature and estimated densities between February 27th and March 2nd 2018 (Cycling #10)

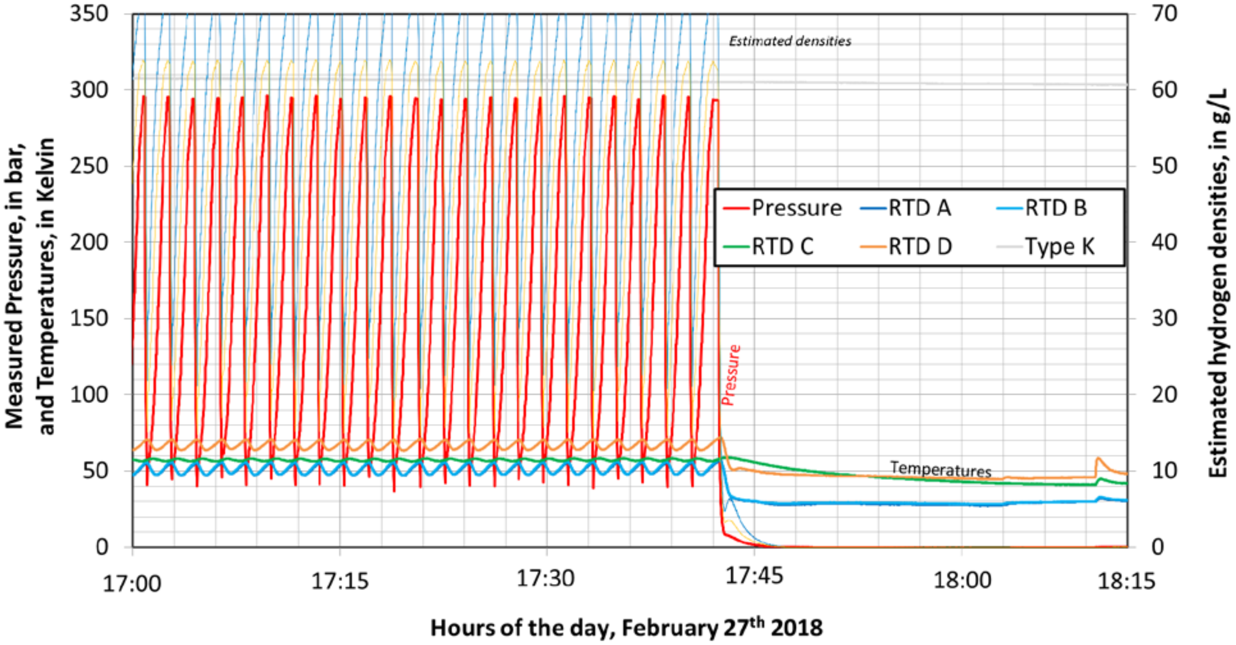


Figure 38: Pressure, temperature and estimated densities on February 27th 2018 (Cycling #10), details

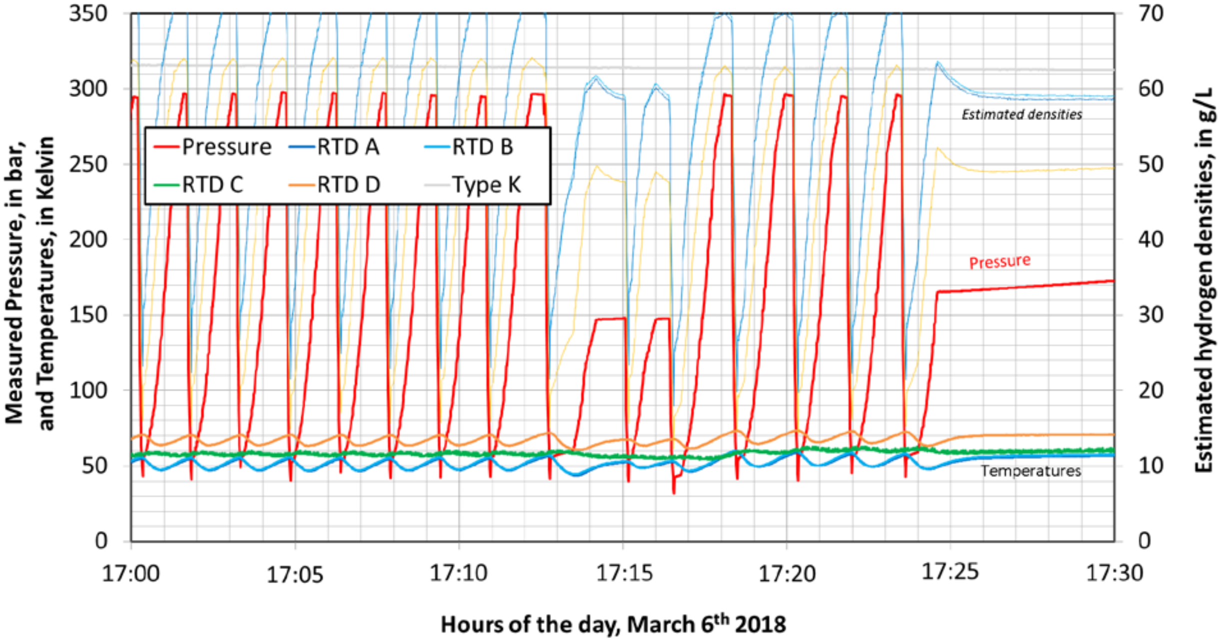


Figure 39: Pressure, temperature and estimated densities on March 6th 2018 (Cycling #11), details

3. LH_2 pump performances

In this section, we present pump performance results measured over the 1,000+ cycles to 300 bar, among which boil-off, pump outlet temperatures, and electricity consumption

3.1. Boil-off fraction and electricity consumption

Boil-off fraction is calculated as the amount of H_2 vented from the 3,300 gallon Dewar (in kg) divided by the amount of H2 dispensed to the vessel (in kg), during the fill. **Figure 40** shows the boil-off fraction for each of the 1,019 fills. It can be seen that for each cycling day (1 through 11), a significant boil-off is always observed at the beginning (4 to 14%), then the boil-off fraction quickly decreases. For example, for cycling day #7 (fill 363 to 563), the boil-off fraction is initially 6% then reaches near 0 within ~15 fills. **Figure 41** shows the distribution of the measured boil-off fractions over the entire 1,019 fills to 300 bar: 40% of the fills had 0 boil-off, while 75% experienced less than 1% of boil-off. The top 10% had more than 10% boil-off. The average electricity consumption for each fill is reported on **Figure 42**: about 1.1 kWh/kg was observed for most of them. It is worth noting that similar performances (boil-off fraction and electricity consumption) were measured before the pump failed (first ~100 fills) and after.

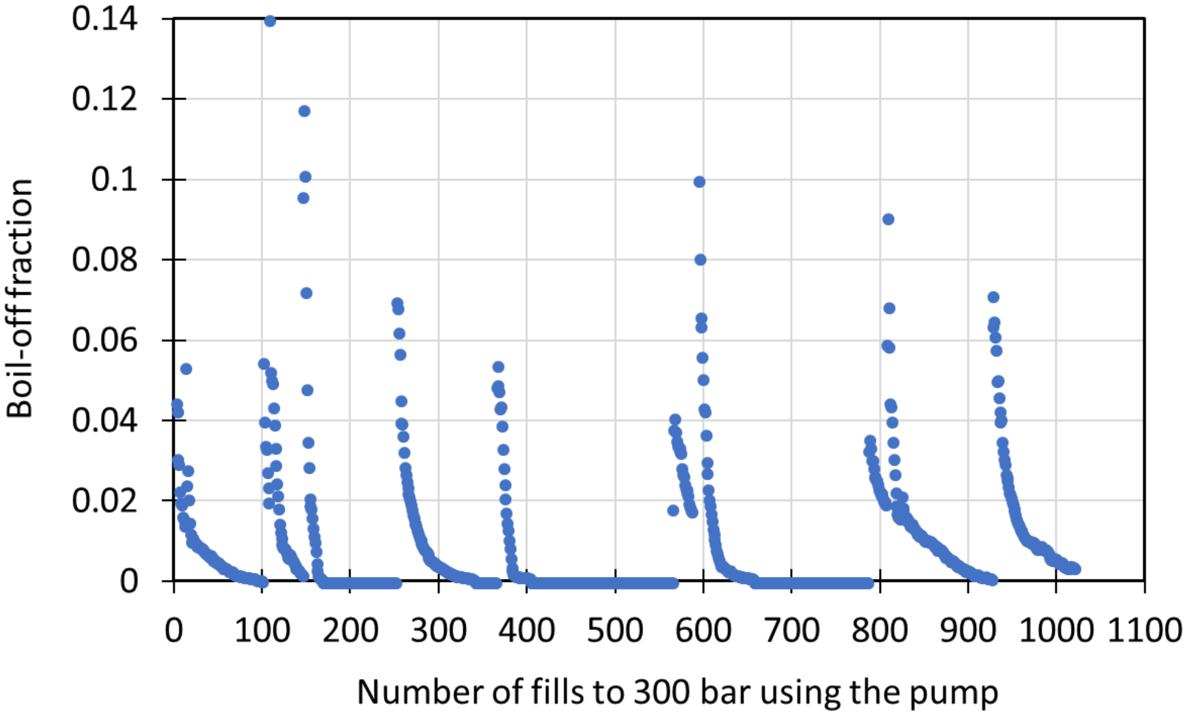
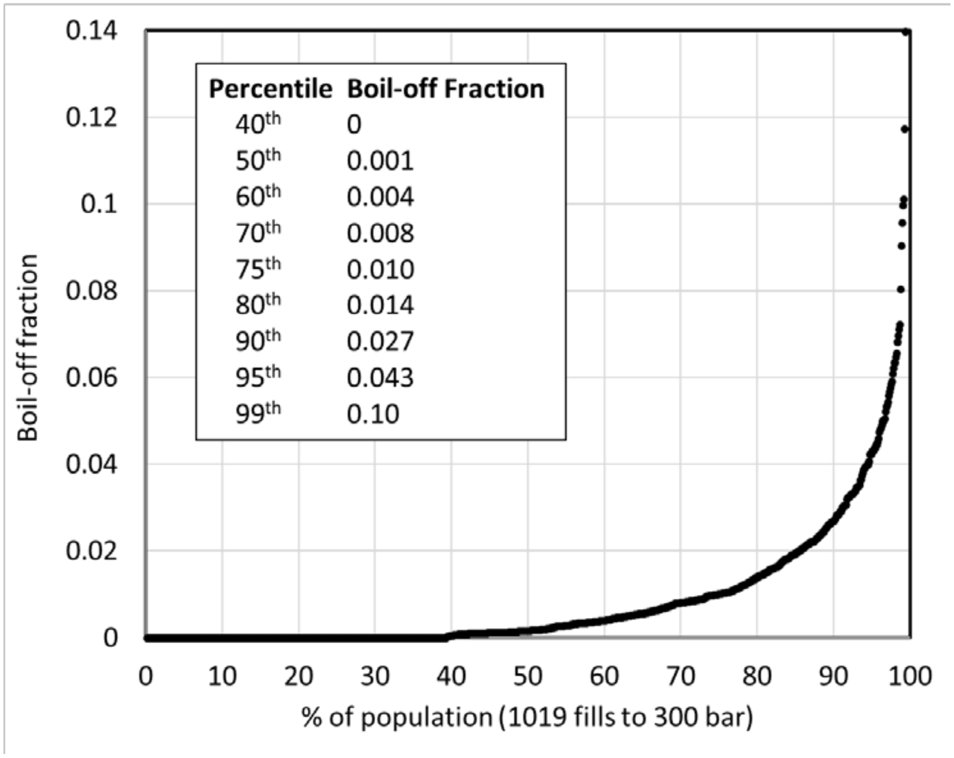


Figure 40: Boil-off fraction for each of the 1,019 fills to 300 bar



Percentile	Boil-off Fraction
40th	0
50th	0.001
60th	0.004
70th	0.008
75th	0.010
80th	0.014
90th	0.027
95th	0.043
99th	0.10

Figure 41: Distribution of boil-off fraction measured during 1019 fills to 300 bar

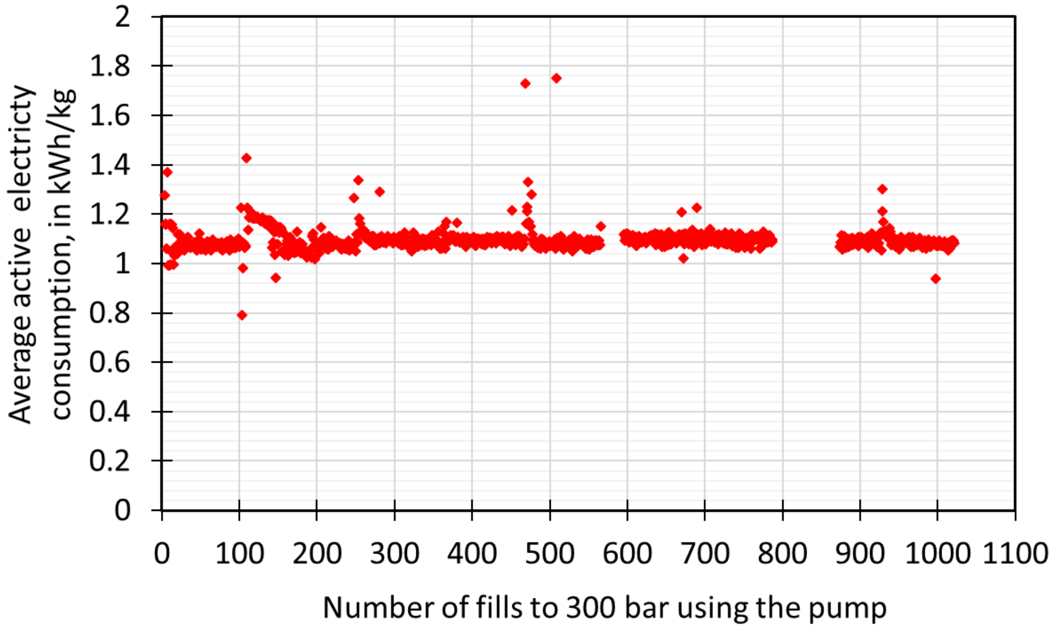


Figure 42: Electricity consumption, in kWh/kg, of each of the 1,019 fills to 300 bar

3.2. Measured hydrogen temperatures

A silicon diode located at the closest non-vacuum jacketed segment of the pump outlet enables to infer the temperature variations of the hydrogen leaving the pump. The temperature sensor is inserted into a copper holder with a round shape, that is then glued on the bare stainless steel high pressure pipe with epoxy, in order to minimize thermal resistance between the hydrogen that flows inside the pipe and the temperature sensor. As such, there is a possible error/delay between the actual temperature of the H_2 and the measured value.

Figure 43 shows the measured pump outlet temperature as a function of pump outlet pressure for different fills during the day (Fills # 1, 25, 50 and 88). All fills are roughly identical in time profile, and it can be seen that the temperature decreases as more and more fills as conducted throughout the day, roughly a 6 hour window. This can be explained by 2 effects: the piping becoming colder and colder during the day, and the increasingly colder LH_2 coming from the Dewar. **Figure 44** shows the measured outlet temperatures and the measured pump vessel temperatures during cycling #2 and #10 (red and blue, respectively). It can be seen that indeed both temperatures decrease during the course of the day (for both cycling days): the incoming LH_2 from the Dewar is increasingly colder, and so is the pump outlet temperature. Interestingly, if we now calculate the corresponding entropy for fills #1 and #88, we realize that although the temperature is *increasing* as a function of pressure (above 100 bar, **Figure 43**), the corresponding entropy is actually *decreasing* with pressure (see **Figure 45**). The pump's isentropic efficiency thus *increases* with pressure, from around 10 J/g.K at 50 bar to almost 4 J/g.K at 300 bar.

As shown on **Figure 3**, the distance between the pump outlet and the prototype vessel (located in the containment vessel) is rather long (100+ ft) and made of foam insulated high-pressure piping. As a result, significant temperature increase is to be expected between those 2 locations, eventually leading to lower H_2 densities than values that would be typically observed should the vessel be located directly at the pump outlet, and/or should better insulation (i.e. vacuum jacketing) used. Using the temperature sensors located the vessel inlet (

Table 3), it is possible to compare the temperatures at the 2 locations during a fill. Of course, those temperatures should not be taken directly "at face value" given all the possible errors (delay, thermal contact resistance at interfaces…) between the H_2 flow and where/how the temperature is actually measured. RTD A is a sensor located on the stainless-steel inlet pipe of the pressure vessel, and the variations of the temperature measured at this location during a fill is plotted on **Figure 46**, together with the values recorded at the pump outlet (black and blue markers, respectively). On this figure, it can be observed that the trends are very similar for the 2 sensors: the temperatures first decrease with pressure up to 100 bar, then slowly increase until 300 bar. On average, an 8 K temperature gap is observed between the 2 sensors. In order to evaluate the accuracy of the measurement from RTD A, its indicated entropy vs. pressure (see **Figure 47**, black symbols) is used as an input for a thermodynamic fill model, assuming a 109 L prototype vessel made of 20 kg of Aluminum and 20 kg of carbon fiber – see **Figure 48**. Interestingly, using 50 bar and 46 g/L as the initial conditions in the vessel (condition experimentally observed at the end of cycling #6, see **Figure 30**), the thermodynamic fill model simulates a final H_2 density slightly above 66 g/L at 300 bar, i.e. thermodynamic conditions observed a few times experimentally (see Cycling #5 and Cycling #9, see **Figure 28** and **Figure 36**). **Figure 48** also shows the expected density if the prototype vessel were located directly at the pump outlet (blue line) from the same conditions, as calculated by the thermodynamic model: a value of 68 g/L should then be measured.

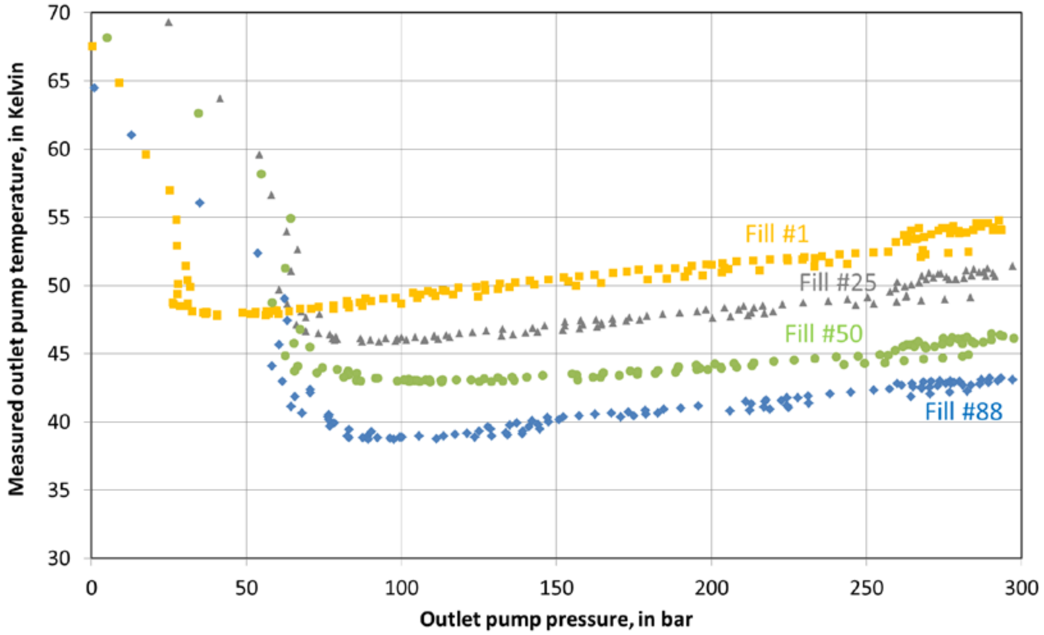


Figure 43: Measured pump outlet temperature vs. pressure on April 12th, 2017

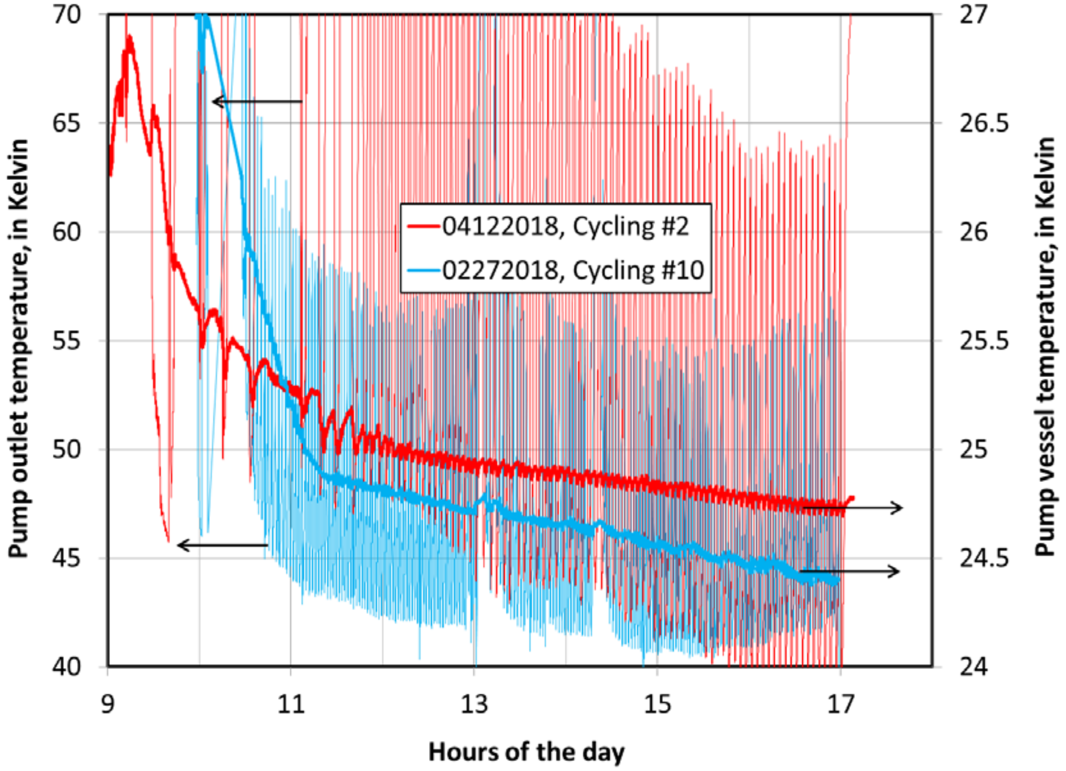


Figure 44: Measured pump outlet temperature (left axis, thin lines) and measured pump vessel temperature (right axis, thick lines) as a function of the time of the day (9 AM to 6 PM) for Cycling #2 (red) and Cycling #10 (blue).

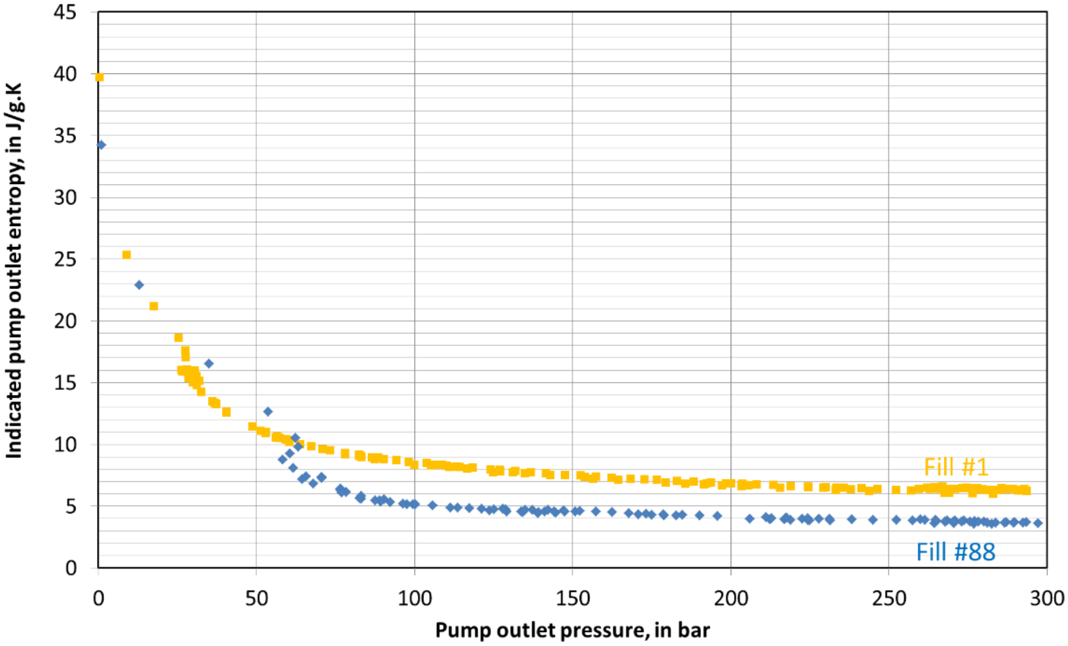


Figure 45: Indicated pump outlet entropy vs. pressure on April 12th, 2017 for fills #1 and #88

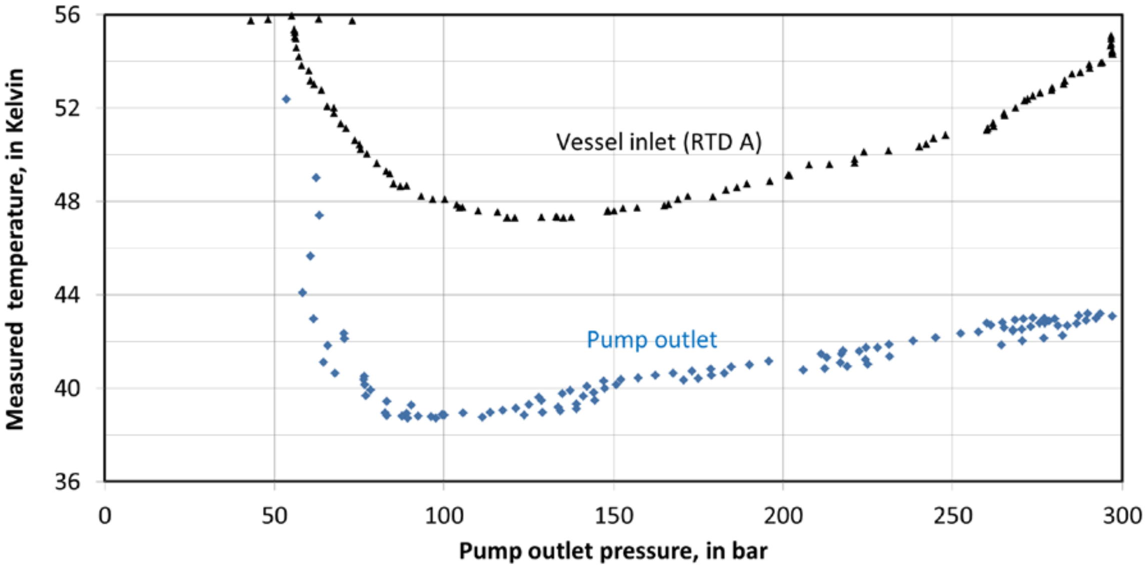


Figure 46: Measured H_2 temperatures at pump outlet (blue) and vessel inlet (RTD A, black) during a fill to 300 bar

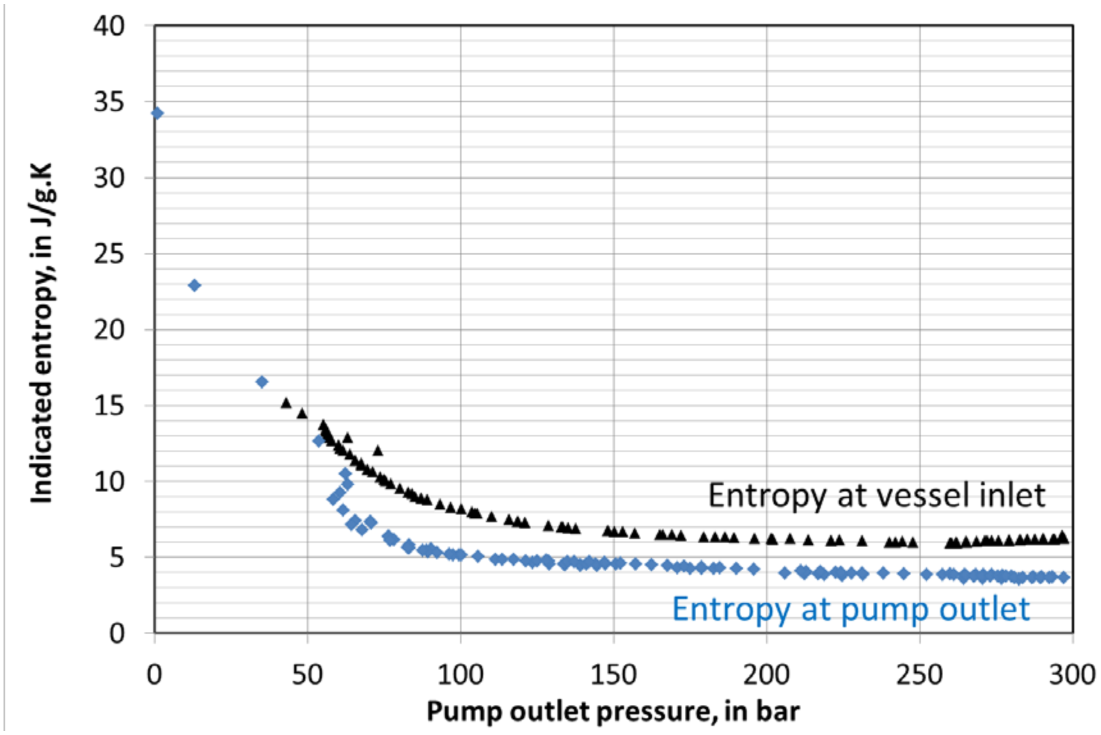


Figure 47: Indicated entropy based on the measured temperature at pump outlet (blue) and vessel inlet (black)

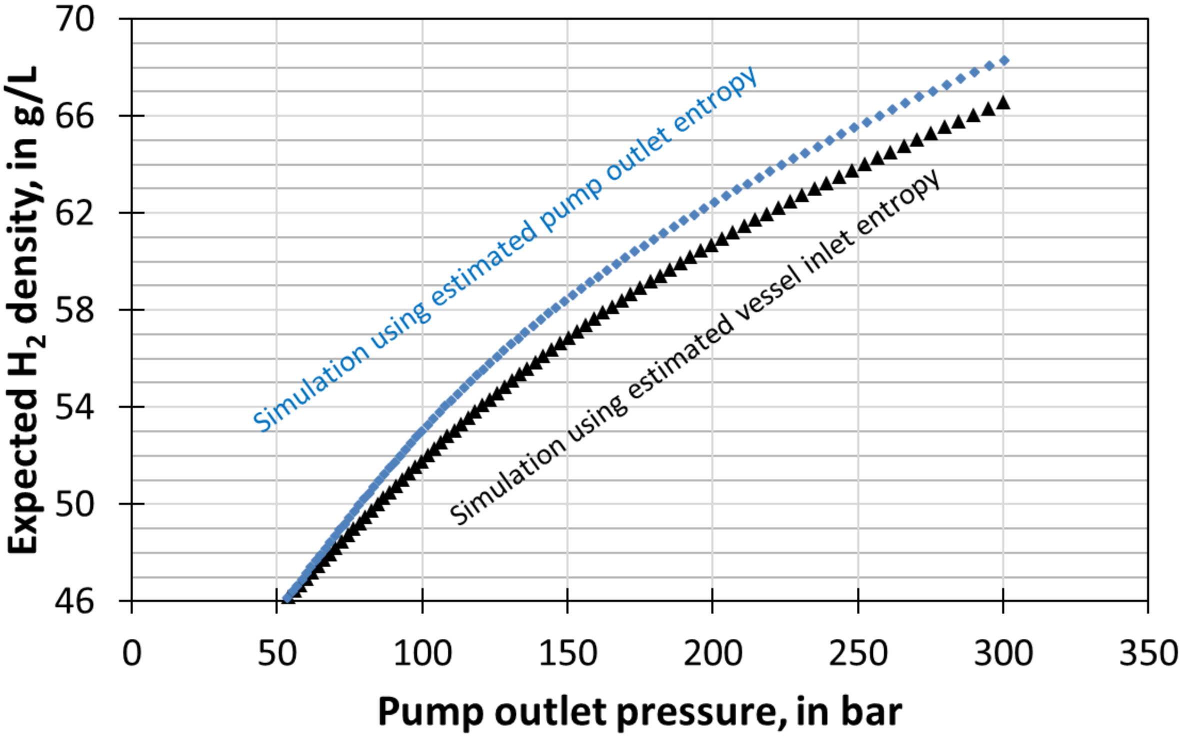


Figure 48: Simulated density in the prototype vessel during a fill from 50 bar, 46 g/L to 300 bar, using either the estimated pump outlet entropy (blue line) or the vessel inlet entropy (black line). The prototype vessel is assumed to be 109 L internal volume, with 20 kg of Aluminum and 20 kg of carbon fiber (masses assumed by LLNL)

3.3.Fill times and flow rates

Additional results on the cycling that was performed are reported here.

First, we show amounts of H_2 for each of the 1,019 fills (**Figure 49**), as calculated from the variations of flow rate during each fill. It was purposely chosen to work with small quantities of H_2 in order to maximize the number of cycles given the limited funding (i.e. time and hydrogen). After the first ~300 fills, it was decided to consistently cycle between 50 and 300 bar, resulting in about 2 kg being dispensed hereafter.

Figure 50 shows the fill time for each fill. For each cycling day, this amount was larger at the beginning of the day (=more H_2 dispensed) as we often started from a vessel initially warm. For a typically cold vessel, it would take about 1.5 minutes to fill the tank.

Data from **Figure 49** and **Figure 50** were used to generate the average fill time shown on **Figure 51**, with values around 1.3 kg/min. This value is less than 100 kg/hr (=1.66 kg/min) as this represents the peak flow rate from the pump, and the pump experiences various ramp up and down throughout each fill.

Time between fills (i.e. time between end of previous fill and beginning of fill) are finally shown on **Figure 52**, varying from 10 minutes at the beginning down to 0.3 minute (20 seconds) …

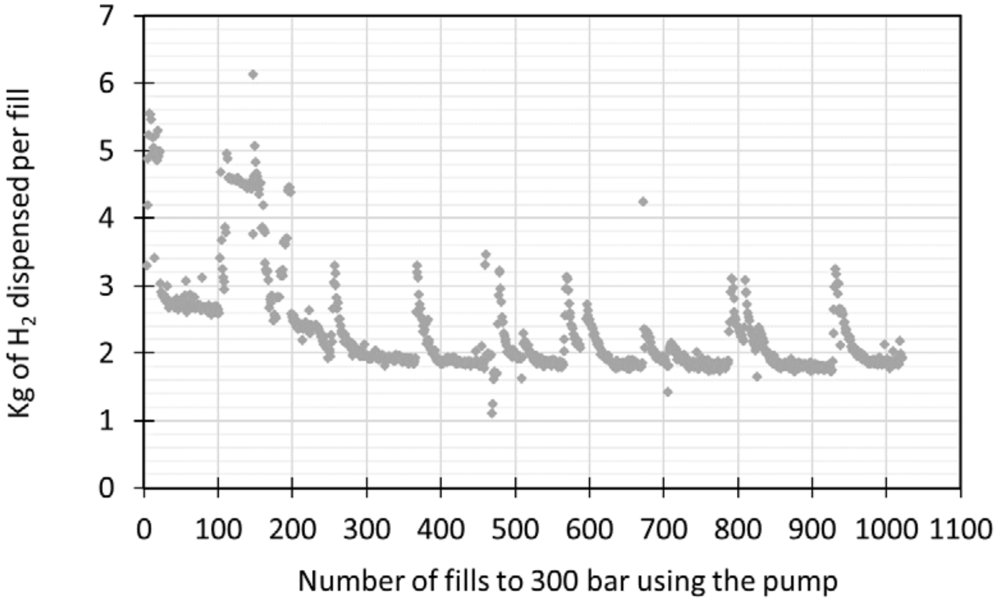


Figure 49: Amount of H_2 dispensed for each the 1,019 fills to 300 bar, in kg

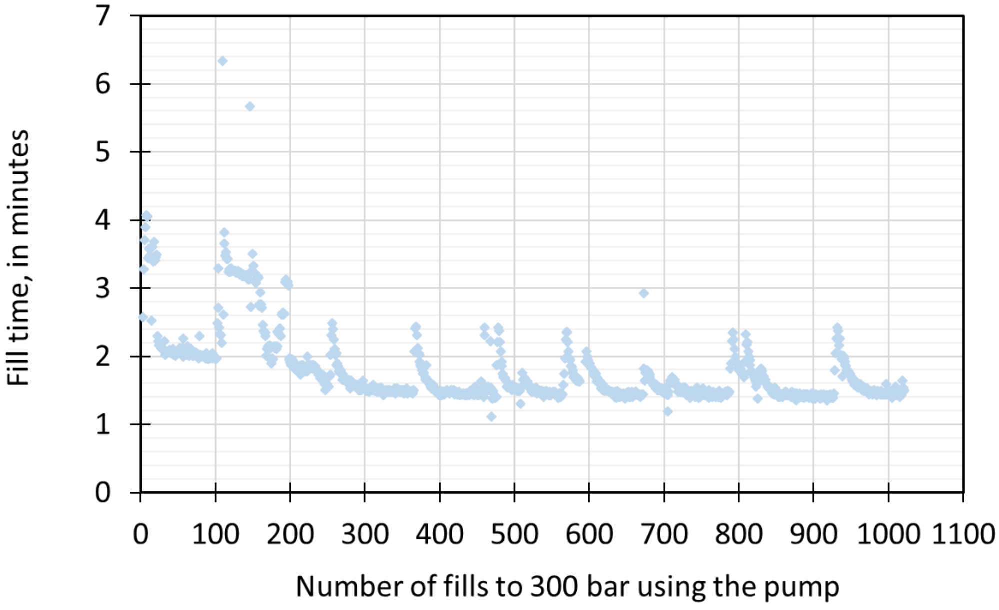


Figure 50: Fill time for each of the 1,019 fills to 300 bar, in minutes

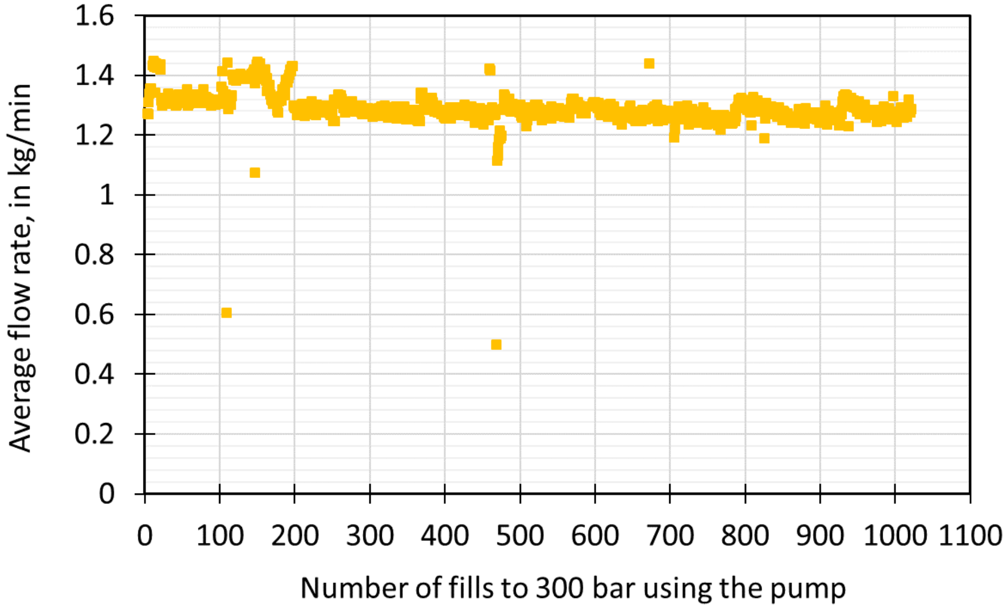


Figure 51: Average flow rate for each of the 1,019 fills to 300 bar, in kg/min

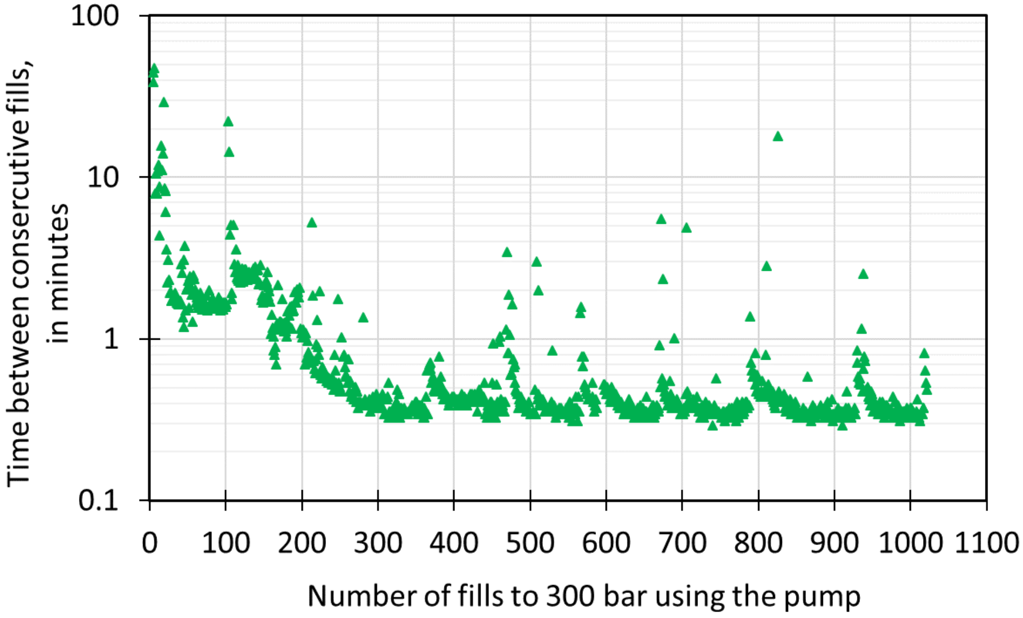


Figure 52: Time between consecutive fills for each of the 1,019 fills to 300 bar.

4. LH_2 pump failure

We report details on the pump failure incident that took place on April 19th 2017.

4.1.Description of the incident

After 7 refueling to 300 bar, the pump could not pressurize more than 180 bar, starting ~ 10:40 AM. The pump kept pumping for almost 15 minutes and no pressurization of the prototype pressure vessel could be observed.

The pump was stopped then through our vent stack alone (no vessel refilling), and it was noticed that the H_2 plume was smaller than usual. At last, the downstream valve was shut down, so that the pump was basically trying to fill a tiny closed volume (=piping alone): the pump was not able to pressurize above ~ 11 bar, although the pump frequency was increased from 60 to 100%.

We performed a few other trials with the downstream valve closed and opened, and we never were able to pressurize more than ~11 bar, even though we ran the pump for a long amount of time. **Figure 53** and **Figure 54** show the data measured by different transducers at the pump when the failure happened, for illustration purposes

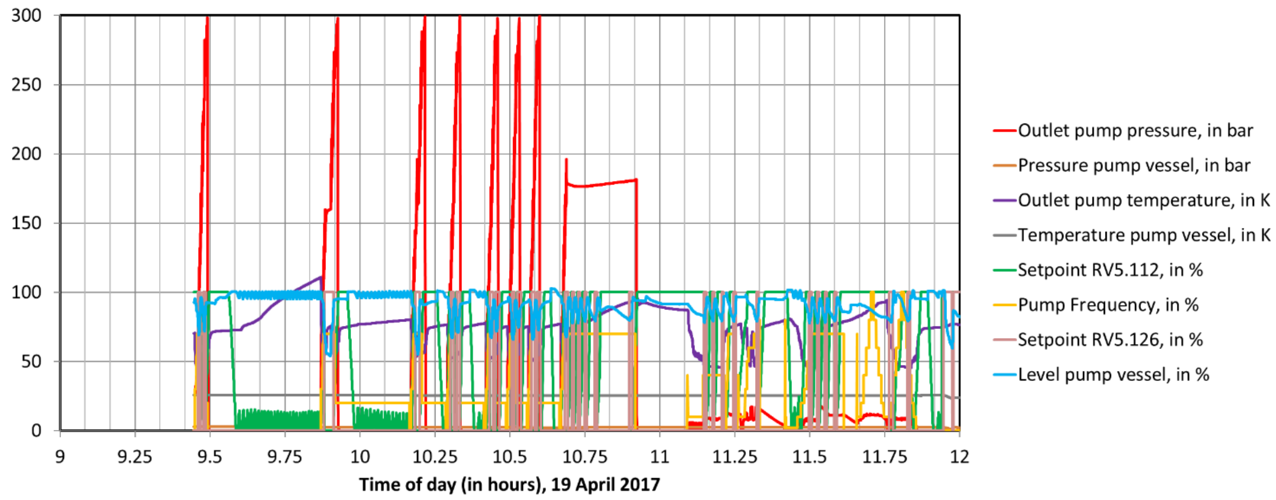


Figure 53: Data measured at the pump on April 19th 2017

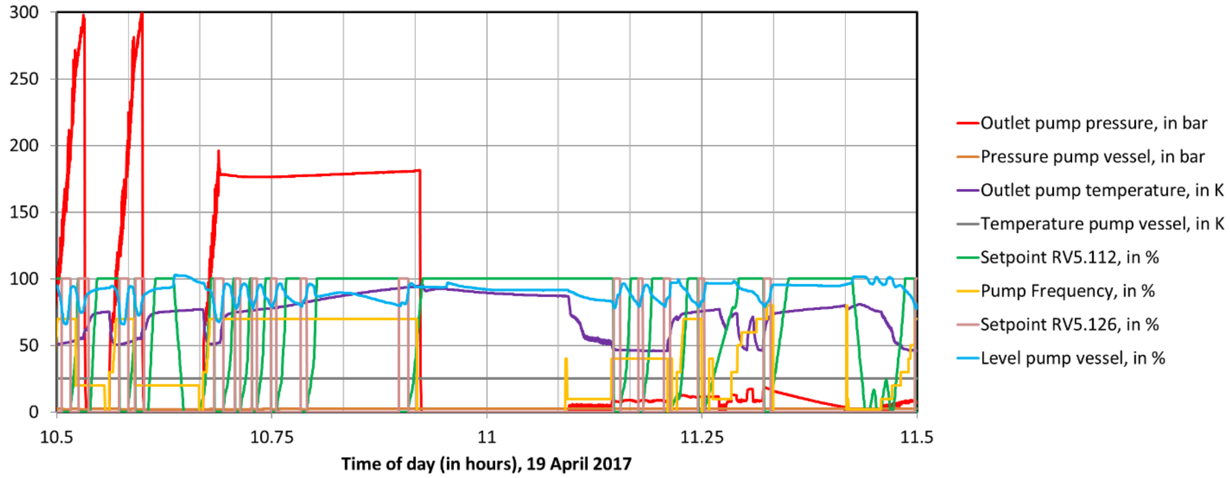


Figure 54: Data measured at the pump on April 19th 2017, details

4.2. Additional testing to identify failure

Based on recommendation from Wilfried Reese (Linde AG), we proceeded with additional testing on April 20th in an effort to assess better the condition of the pump, by checking pressure loss in the system. The piping downstream the pump was backfilled with high purity H_2 at up to 100 bar - see setup on **Figure 55**, and it was observed the system was losing pressure at a rate of 30 bar per 10 then 15 minutes – see red line on **Figure 56.** The increasing pump vessel pressure (blue line) was attributed to LH_2 self-pressurization in the pump vessel: indeed, the vessel was full of LH_2 and all valves were closed during the pressure test for safety purposes. Based on the test results, it was decided that the pump underwent a major failure and that it should thus be sent back to the Linde AG facilities in Germany for further testing and repair.

Figure 55: Picture of the setup used on April 20th 2017 to test the pump

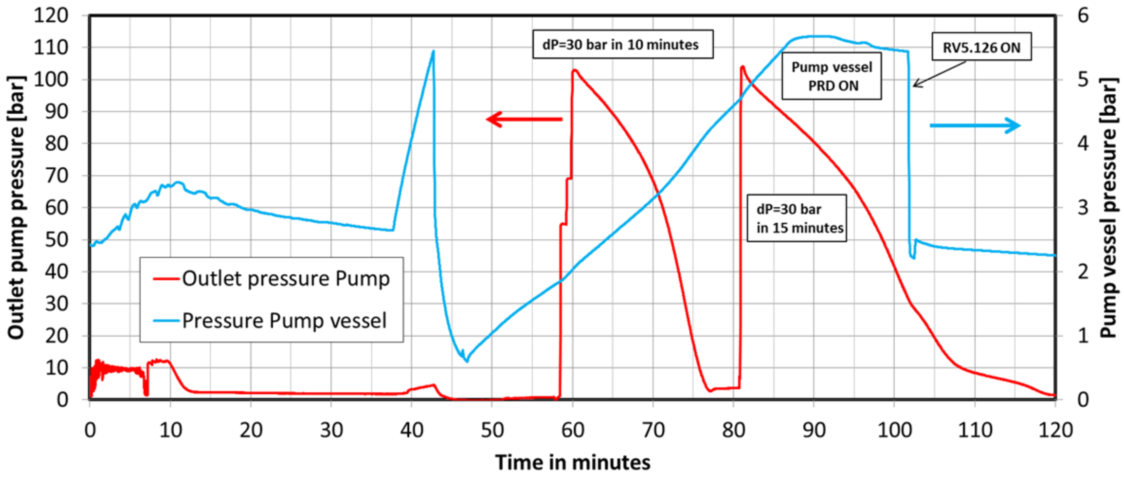


Figure 56: Experimental results of the test carried out on April 20th 2017.

Conclusions

The cycling of the BMW prototype pressure vessel at LLNL was conducted between April 2017 and March 2018. No degradation of the vessel was observed after 1000+ cycles to 300 bar. We summarize below the main results:

- 1019 cycles to 300 bar were carried out with the LH_2 pump on the prototype pressure vessel, and an extra 18 pressure cycles (including 11 to 350 bar) were performed by warm-up only; for a total of 1037 pressure cycles to and above 300 bar,
- Most of the cycles were performed between 50 and 300 bar, with measured top composite surface temperatures (RTD D) between 80 and 100 K, and measured liner temperatures as low as 50 K,
- An estimated maximum density of 66.6 g/L of H_2 at 300 bar could be achieved. Given the long foam insulated path (100+ ft) between the pump outlet and the vessel inlet, the H_2 reached out to the vessel at warmer temperatures than typically expected for a cryo-compressed fill: a delta measured as high as 8 K,
- Our thermodynamic fill model indicates that a maximum density of 68 g/L could be reached if the vessel were located directly at the pump outlet and were filled from the same density at 50 bar,
- Pt-based Resistance Temperature Detectors (RTD) repeatability cycled between cryogenic and room temperature over a long period of time (~11 months) and in a non-temperature controlled environment (sensors located in a containment vessel, itself located outside) did not seem to experience any loss of accuracy nor precision, which make them really good candidate for this type of testing.

In addition to the information obtained on the cyclability of cryogenic pressure vessels, pump durability was also tested, with the main outcomes summarized below:

- No degradation of the pump performances was measured throughout the cycling period (1,019 cycles), in terms of outlet temperature, energy consumption and boil-off. In addition, the pump seems to behave similarly before and after the failure,
- Between 50 and 300 bar, the pump seems to increase its entropic efficiency with pressure, going from around 10 g/J.K near 50 bar down to almost 4 g/J.K. This is worth noting as one would expect *decreasing* isentropic efficiency with pressure,
- It could be observed that the pump outlet temperature decreased during the day when the pump was continuously used. This can be explained by 2 phenomena working in the same direction: the piping becoming colder and colder during the day, and the increasingly colder LH_2 coming from the Dewar.

Acknowledgements

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Disclaimer

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