Pool-Experiments (WP3.4 and WP4.4)

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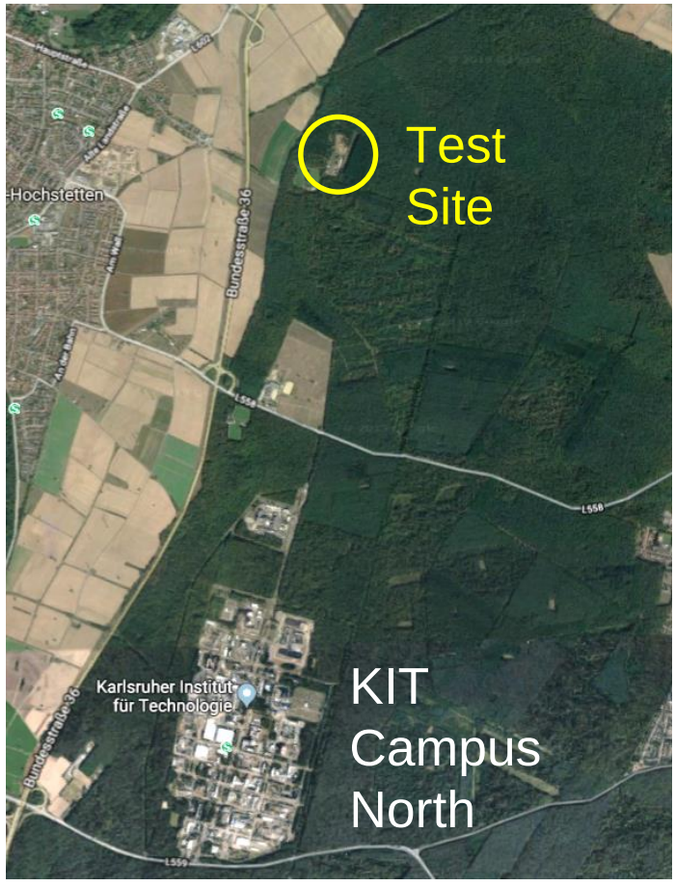
Pre-normative REsearch for Safe use of Liquid HYdrogen

E3.4 and E4.4 Pool Experiments

- **General aim**
  - Investigation of the evaporation rate from an LH2 pool and the cold gas mixing phenomena in the near field above the pool.
  - Measurements also aimed to investigate oxygen, nitrogen, moisture carry-over within the pool and the potential for oxygen enrichment in the gas,
  - With a special ventilation system cross wind conditions should be simulated.
  - It was attempted to ignite the mixtures over different ground materials (solid-liquid-porous) and in different ignition positions
  - The measurements included BOS imaging as well as temperature and concentration profile in gas, and fast remote pressure measurements.

E3.4 and E4.4 Pool Experiments

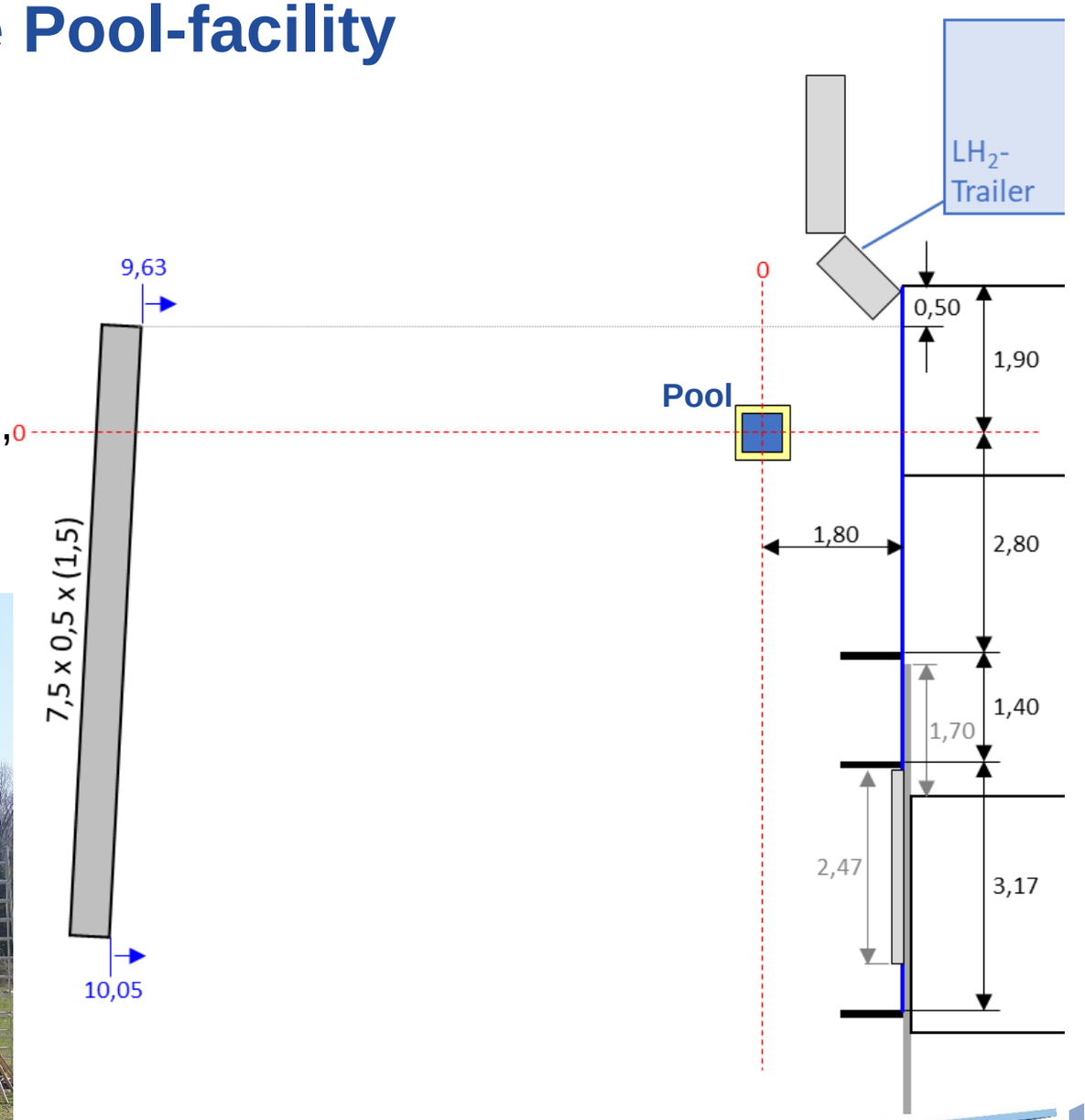
- Already in the early planning phase of the experiments it was obvious that large quantities of LH2 will be evaporated in the pool experiments,
- Due to safety considerations it was decided that these experiments cannot be performed at KIT-HyKA,
- Another Free Field Tests Site was found close to KIT-Campus North,
- When LH2 became available (only few days before lockdown in France and Germany) the LH2-Trailer from Air-Liquide was parked on this site and all experiments with LH2 were performed there, (during COVID-19 lockdown in Germany).



E3.4 and E4.4 Pool Experiments

Description of the Pool-facility

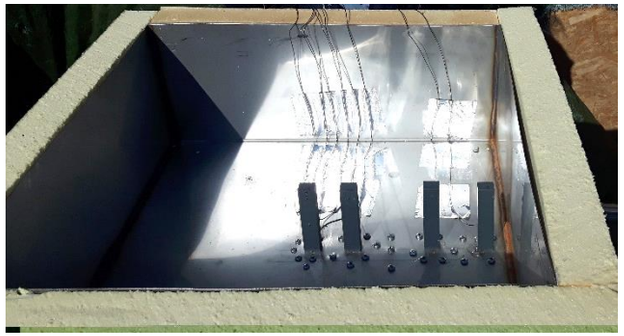
- **General Set-Up**
  - Pool positioned on table in free field,
  - Position governed by 2 parameters:
    - Length of super-insulated hose provided by AL together with trailer,
    - Geometrical parameters for BOS-observations.

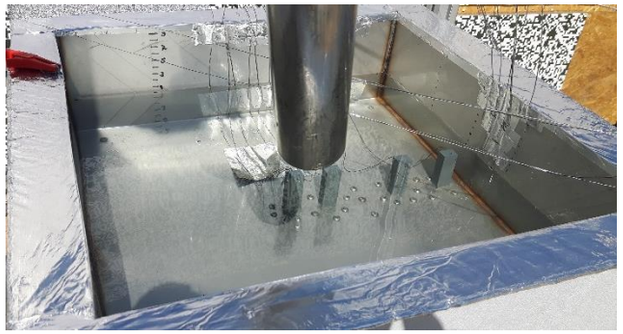


E3.4 and E4.4 Pool Experiments

Description of the Pool-facility

- **General Set-Up of the Pool**
  - Inner dimensions: 50 x 50 x 20 cm (L x W x H),
  - Insulated with styrofoam plates on bottom and sides,
  - Filled with substrate up to half the height (10 cm),
  - 4 different substrates used:
    - Concrete
      (prepared already more than 1 month prior to first experiment),
    - Sand (equipped with baffle plate),
    - Gravel (gravel removed for tests with water),
    - Water (gravel pool emptied for tests with water).





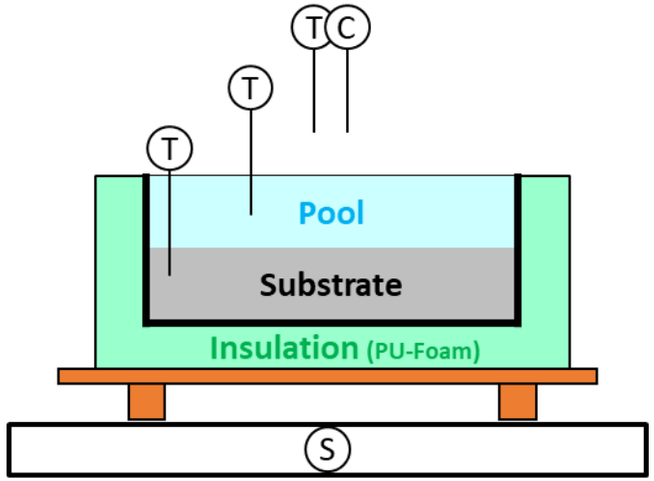
E3.4 and E4.4 Pool Experiments

Description of the Pool-facility

- **Set-Up and Instrumentation**

Every pool was equipped with:

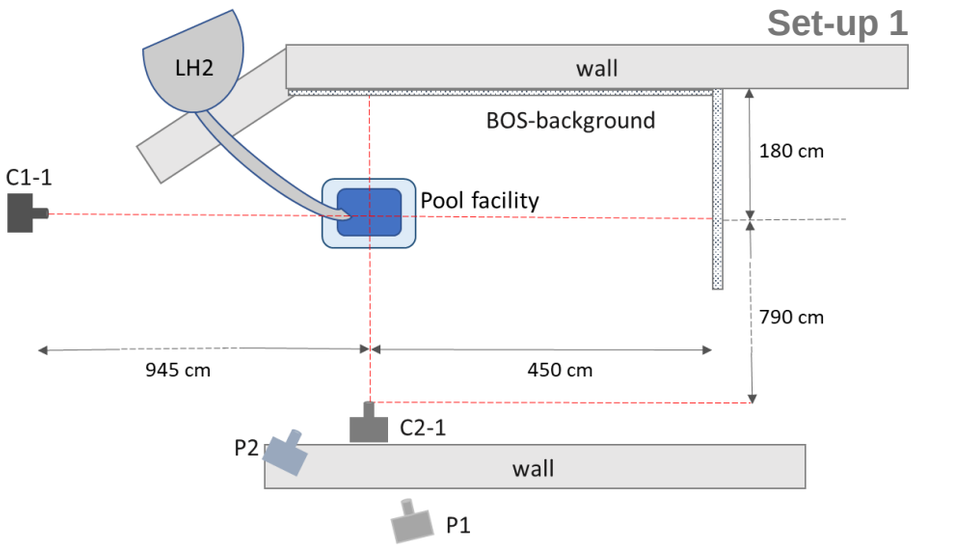
- Palette for transport,
- Scales for weight measurement of H2-pool,
- 8 Thermocouples in substrate,
- 6 Thermocouples in pool,
- 10 Thermocouples above pool,
- 3 H2-concentration measurement positions above pool,
- Experiments were observed with up to 5 cameras,
- Ambient wind conditions were recorded using an anemometer.

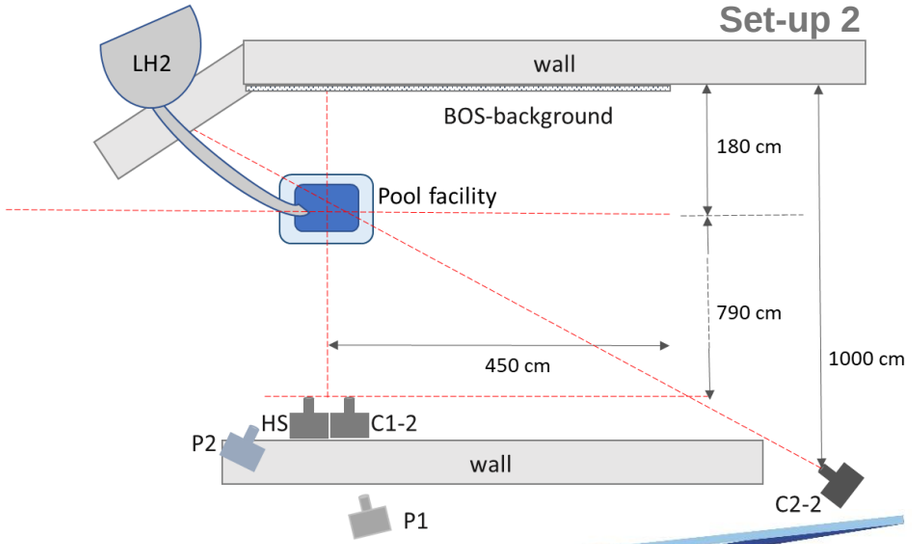


E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

- **Setup for Optical Observation**
  - Up to five cameras in two setups were used during pool-experiments:
    - CANON EOS5D Mark I **(C1)** resolution 5616 x 3744 pix
    - CANON EOS5D Mark II **(C2)** resolution 5616 x 3744 pix
    - Panasonic HC-V800 **(P1)** resolution 1920 x 1080/60p
    - Panasonic Hc-v500/Hc-v500M High-Definition camcorder **(P2)** resolution 1920 x 1080/60p,
    - PHOTRON FastCAM SA 1.1 **(HS)** (only in ignited experiments) resolution 1024 x 1024 pix frame rate 1000 fps, 2000 fps, 5000 fps.





E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

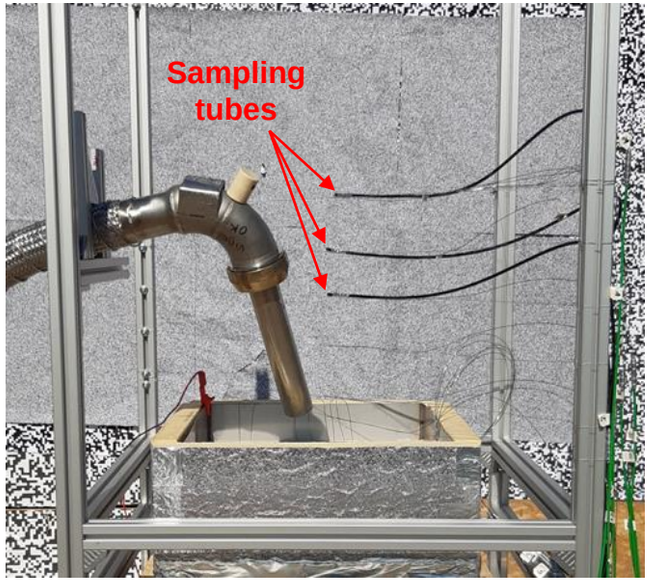
- **Weight measurements**
  - **S** Weight of complete pool:
    Manufacturer: Mettler-Toledo, Type: PBA430x
    Range: 0 - 150 kg, Accuracy: 0.006% FS.
  - To enable weight measurements the complete pool together with transport palette was placed on scales.
  - Efforts were made to eliminate influences of wires and hoses. So complete set-up for measurements above the pool as well as the LH2-hose were fixed to the supporting table of the pool.

Weight measurements had to be recorded separately due to output format of scales.
Maximum measurement frequency of scales is 2 Hz, no changes possible due to lack of possibility to change weighing procedure performed by scales interface.

E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

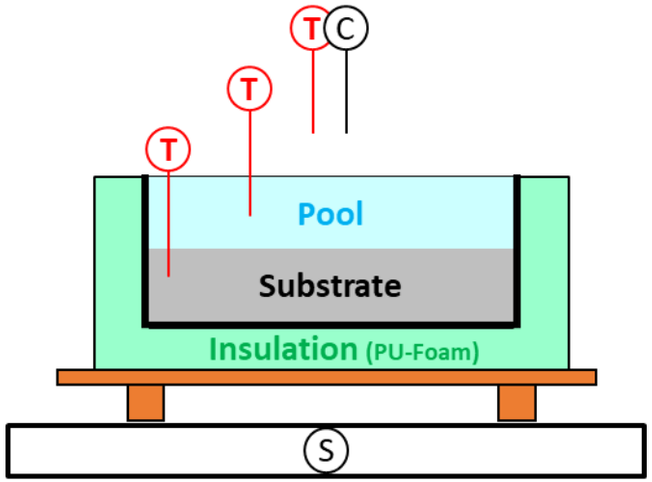
- **H2-concentration measurements (only E3.4)**
  - **CH35, CH45, CH55** H2-concentration above pool (in central position in heights of 35, 45 and 55 cm):
    Manufacturer: Messkonzept, Type: FTC300,
    Range: 0 - 100 Vol% H2, Accuracy: < 1% FS.
  - Procedure: Gas samples are continuously transported from sampling position to sensor through tiny plastic tube (do = 4 mm, di = 2.5 mm, l = 3.0 m) by pump downstream the sensor (one pump for all sensors),
  - Sensor measures H2-concentration continuously, but with some time delay,
  - Same sensors, same procedure and same problems with H2-concentration measurements as in DisCha- and Cryostat-experiments,
  - Due to large safety distance and necessity to warm gas prior to analysis long tubes were necessary, so time delay to first reaction of H2-sensors is 30 s in these tests.
  - No fast flows perpendicular to tube end expected, so horizontal tube cuts were used.



E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

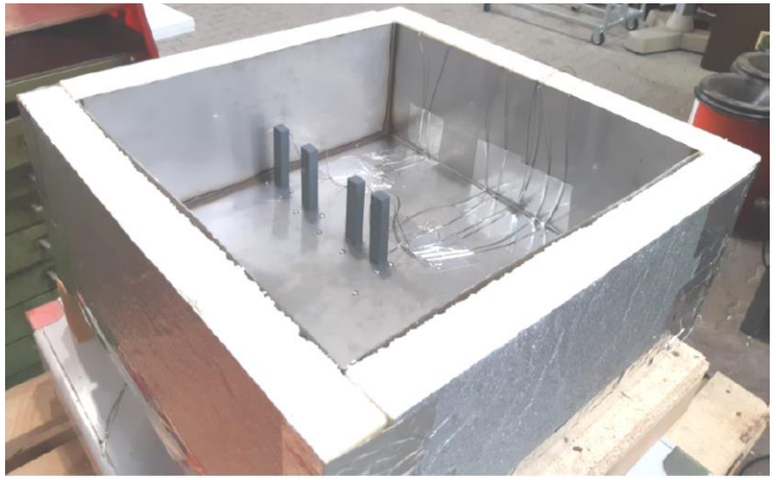
- **Temperature measurements**
  - All measurements with thermocouples (TCs) fabricated in same batch: Manufacturer: KIT-Workshop, Type: Type K, d = 1.00 mm, Accuracy: 1.66 K
  - Temperatures in substrate:
    - 8 TCs positioned in pool prior to substrate filling,
    - TCs in same position in all series,
    - TCs remained with this pool until end of series.
  - Temperatures in pool:
    - 6 TCs positioned on sidewall of pool after filling with substrate,
    - TCs in same position in all series,
    - TCs remained with this pool until end of series.
  - Temperatures above pool:
    - 10 TCs positioned on thin wires above pool,
    - same TCs in unchanged position for all pools.

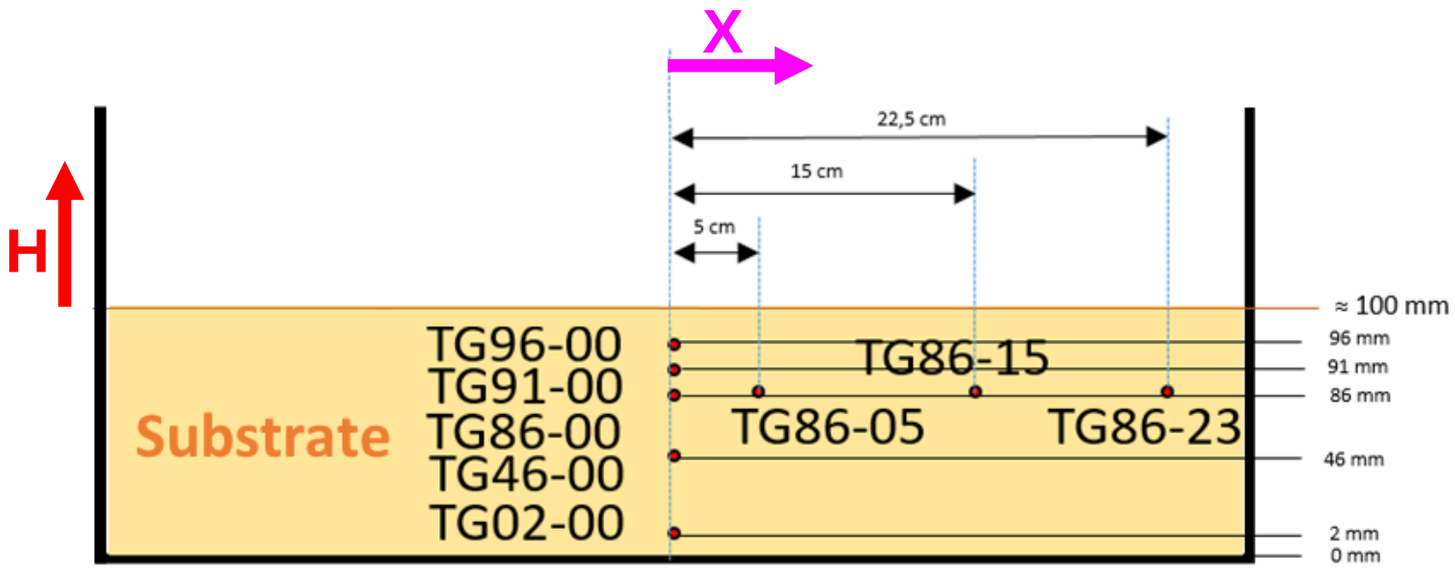


E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

- **Temperature measurements**
  - 8 Temperature measurements in substrate (Positions fixed using plastic holders):
    - 5 Positions on the vertical pool centerline,
    - 3 Positions arranged in line on one pool axis,



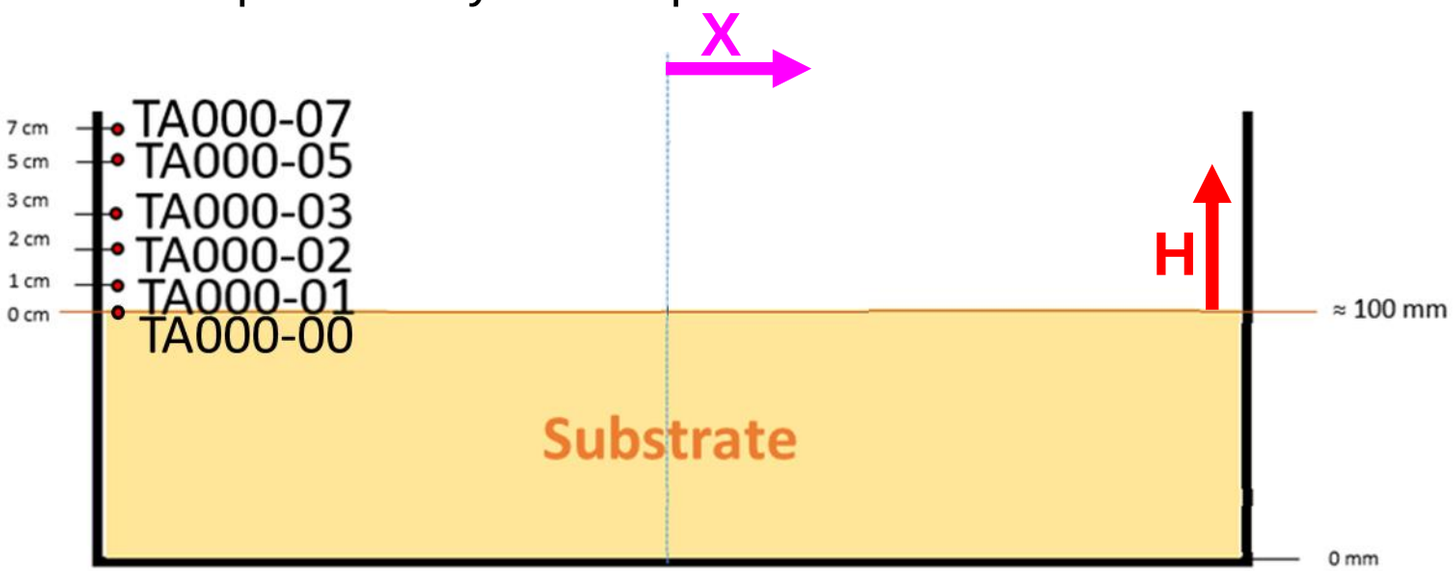


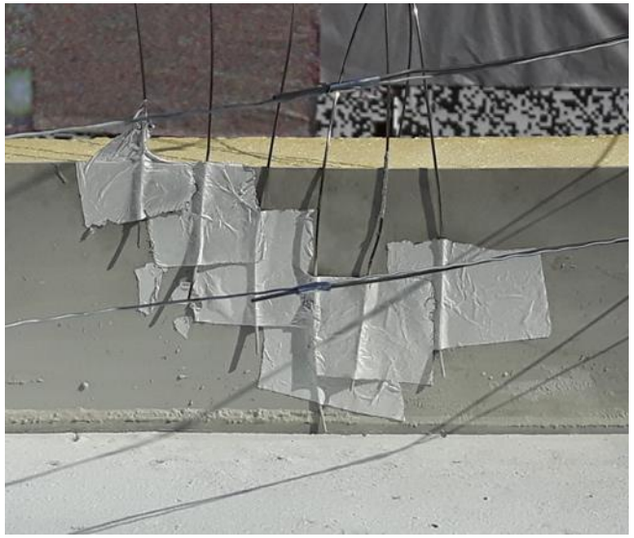
Name	H [cm]	X [cm]
TG02-00	-98	0
TG46-00	-54	0
TG86-00	-14	0
TG86-05	-14	5
TG86-15	-14	15
TG86-23	-14	22,5
TG91-00	-9	0
TG96-00	-4	0

E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

- **Temperature measurements**
  - 6 Temperature measurements in pool (Positions fixed using tape),
  - Tips of TCs were bent into direction of pool center to avoid contact with wall,
  - Positions were checked and, if necessary, readjusted prior to any new experiment.



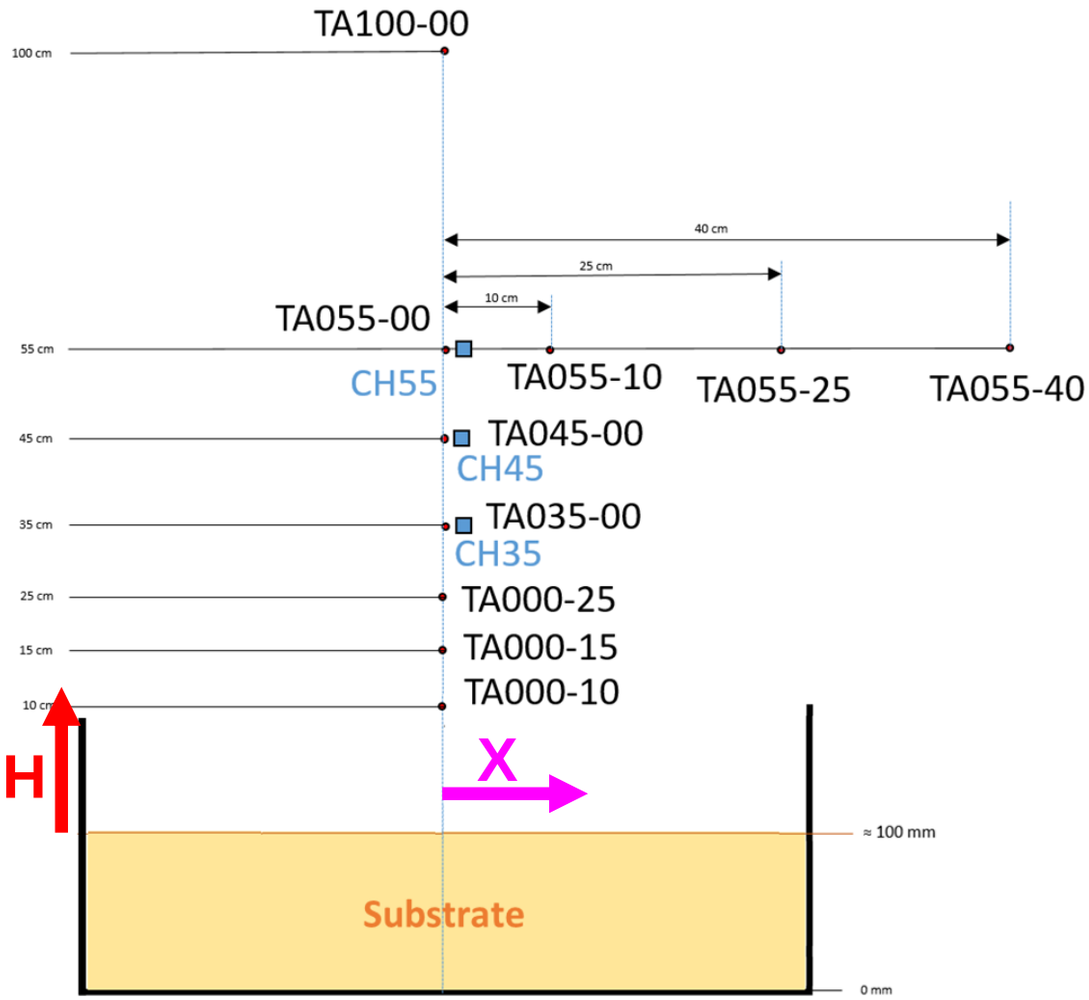


Name	H [cm]	X [cm]
TA00-00	0	-25
TA00-01	1	-25
TA00-02	2	-25
TA00-03	3	-25
TA00-05	4	-25

E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

- **Temperature measurements (only in E3.4 unignited tests)**
  - 10 Temperature measurements above pool (Positions fixed using thin wires):
    - 7 Positions on the vertical pool centerline,
    - 3 Positions arranged in line on one pool axis (one of TCs outside pool).



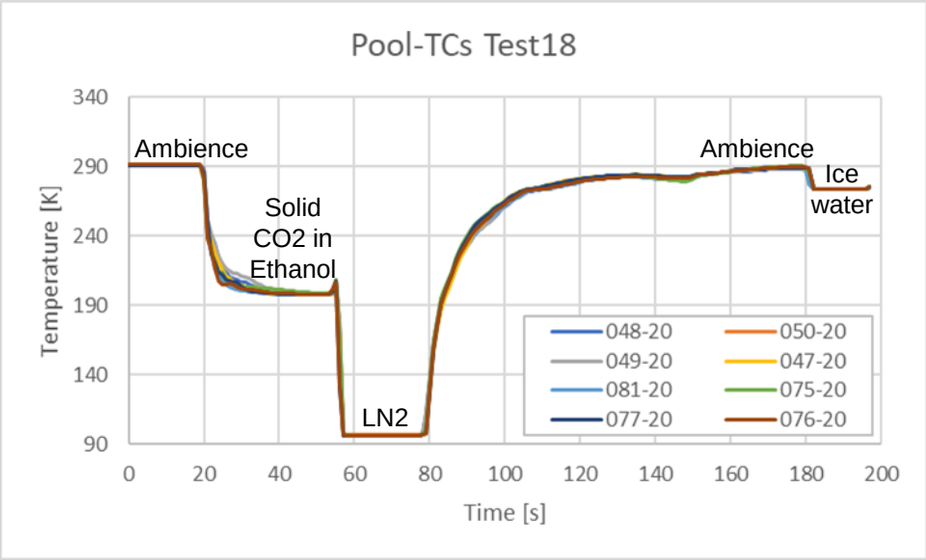
Name	H [cm]	X [cm]
TA000-10	10	0
TA000-15	15	0
TA000-25	25	0
TA035-00	35	0
TA045-00	45	0

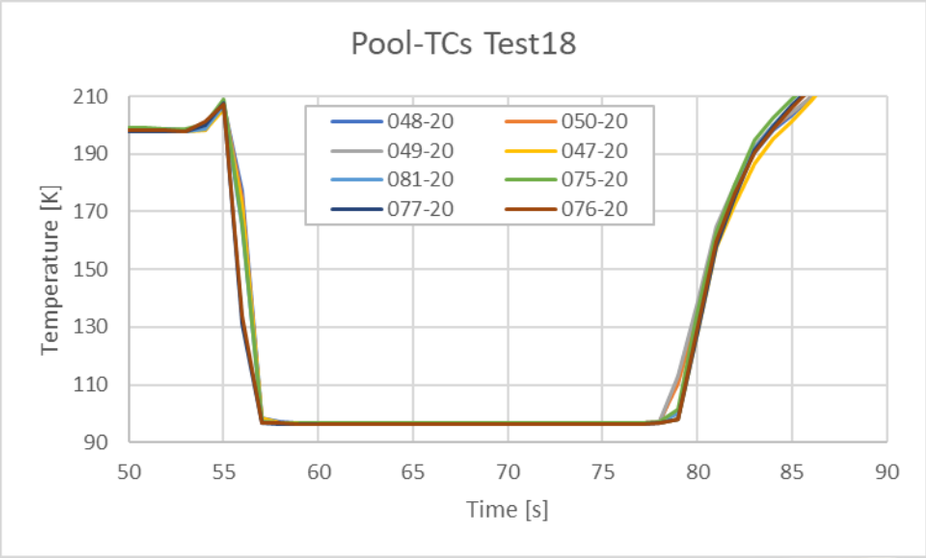
Name	H [cm]	X [cm]
TA055-00	55	0
TA055-10	55	10
TA055-25	55	25
TA055-40	55	40
TA100-00	100	0

E3.4 and E4.4 Pool Experiments

Instrumentation of the Pool-facility

- **Temperature measurements**
  - All thermocouples were fabricated from same batch and all were tested in LN2.
  - For some TCs more elaborated tests including Ice water and Dry Ice (solid CO2) in Ethanol were performed,
  - All TCs showed very similar behavior,
  - LN2 temperature was measured to be T_{LN2} = 97 K (+/- 1 K) by all thermocouples,
  - Systematic error at LN2-Temperature is 20 K,
  - **Important observation:** measured temperature reaches very fast a very stable value when exposed to liquid medium.





E3.4 and E4.4 Pool Experiments

Data of Pool Experiments

- **Signal Express (SE) Data**
  - Usually three SE-data files were generated in one experiment,
  - All files of an experiment were transformed into Excel-sheets (Scales data (2 columns) copied to sheet with temperatures),
  - All Excel sheets of one experiment were grouped in one Excel-file which is named with the date and the Pool-ID.

File	Sheet	Content
20200427-Gravel04	20200427-Gravel04-MW	H2-concentration, Ambience, Trigger (10 Hz)
	20200427-Gravel04-TE	Temperatures (1 Hz), Trigger and two separate columns with Scales data (1 Hz)

- **Fast data acquisition system (Imtech)**
  - Due to data size fast records are stored in separate file with extension “fast” in name.

Sheet	Content
20200427-Gravel04Fast	Fast pressure record (100 kHz), Sound-level, Trigger

Unignited Pool-Experiments (WP3.4)

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Pre-normative REsearch for Safe use of Liquid HYdrogen

E3.4 Unignited Pool Experiments

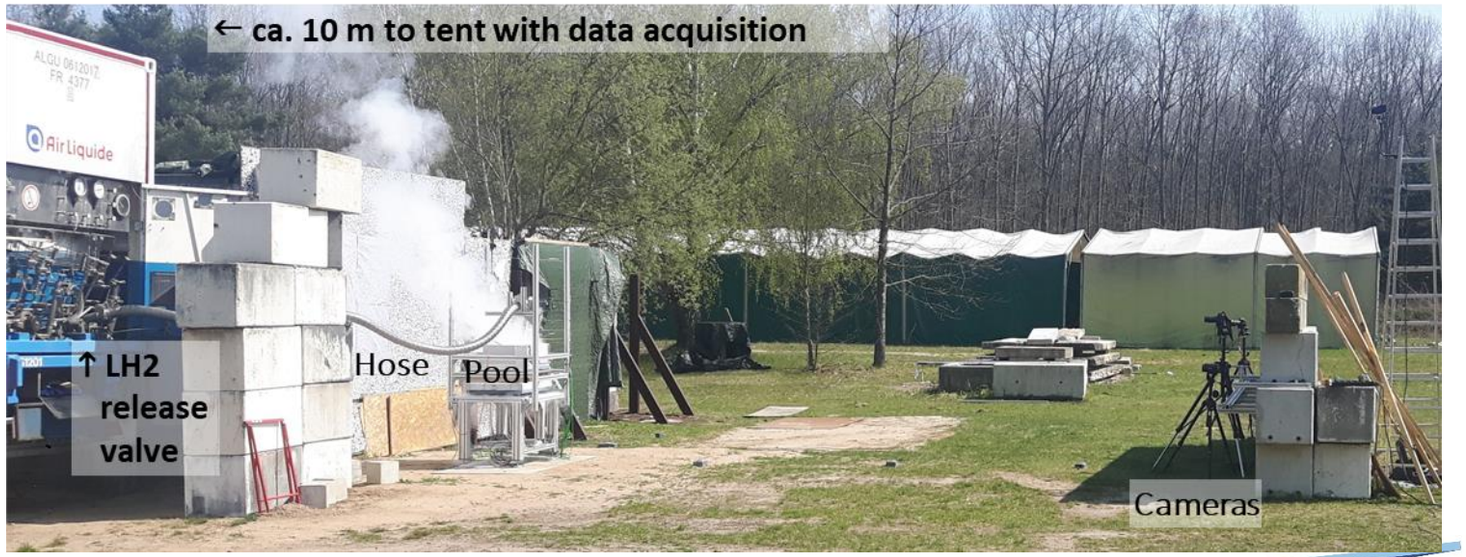
Test Matrix

- **Unignited Pool Experiments (E3.4)**
  - In total 10 unignited experiments were performed with the Pool-facility,
  - Experiments performed with 4 substrates (concrete, sand, gravel, water),
  - 4 experiments performed with “artificial wind” of known velocity and direction.

Date	Substrate	Conditions	Procedure	Comments
20.03.2020	**Concrete01**	Natural	2 Fillings	No scales data (Not used)
24.03.2020	**Concrete02**	Natural	3 Fillings	
08.04.2020	**Gravel01**	Natural	3 Fillings	
09.04.2020	**Sand01**	Natural	3 Fillings	
15.04.2020	**Sand02**	Wind	3 Fillings	No natural wind data
16.04.2020	**Sand03**	Wind	3 Fillings	
17.04.2020	**Concrete03**	Wind	3 Fillings	
22.04.2020	**Gravel02**	Natural	3 Fillings	Gas-Samples
23.04.2020	**Gravel03**	Wind	3 Fillings	Gas-Samples
23.04.2020	**Water01**	Natural	3 Fillings	

E3.4 Unignited Pool Experiments

- **Test procedure Unignited Pool Experiments (E3.4)**
  - Hose was positioned and fixed above pool,
  - Data acquisition (LabView) in tent was started manually and then controlled remotely (from shelter in approx. 100 m distance) until end of experiment, cameras were started manually,
  - LH2-release was started manually (always to approx. the same degree of valve opening) at trailer but stopped remotely,
  - When pool had evaporated following release was again started manually (after safety check with hand held H2-sensor) and stopped remotely,
  - Fast data acquisition was started prior to every LH2-release initiation (waiting for trigger).
  - Usually pool was filled three times in one experiment.

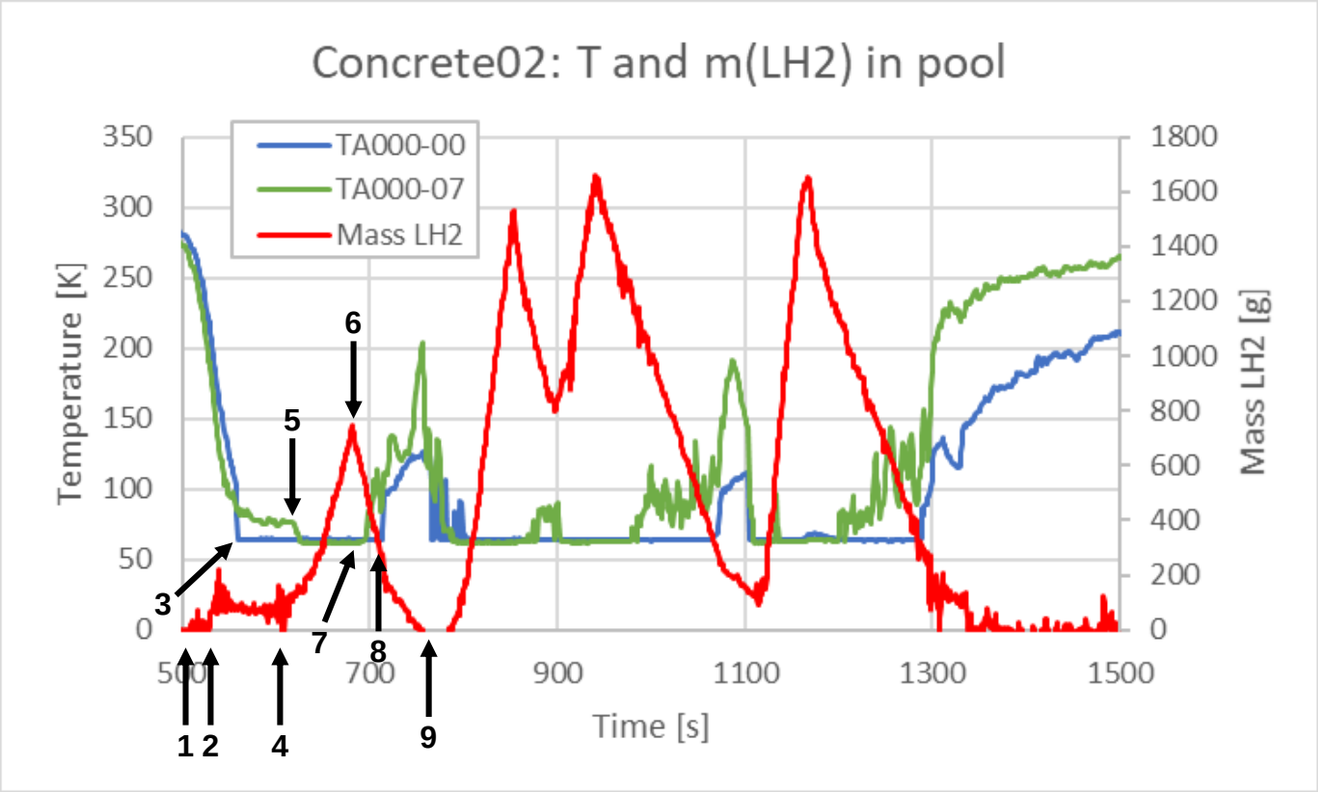


E3.4 Unignited Pool Experiments

Experiment Concrete Pool02

- **Measured temperatures in Concrete Pool and LH2 masses (I)**
  Graph shows temperature at substrate surface (T00, blue) and 7 cm above surface (T07, green) and LH2-mass (Mass, red),

1. Experiment starts with gaseous H2-release (no mass-increase, temperature-decrease),
2. First liquid release produces slight mass-increase,
3. Pool formation starts when T00 becomes constant, but all LH2 still evaporates until weight increases (4),
5. pool height reaches 7 cm when T07 becomes constant (but pool is still boiling),
6. LH2 release stopped,
7. Pool height falls below 7 cm,
8. Pool almost empty (T00 increases)
9. LH2 release re-opened.

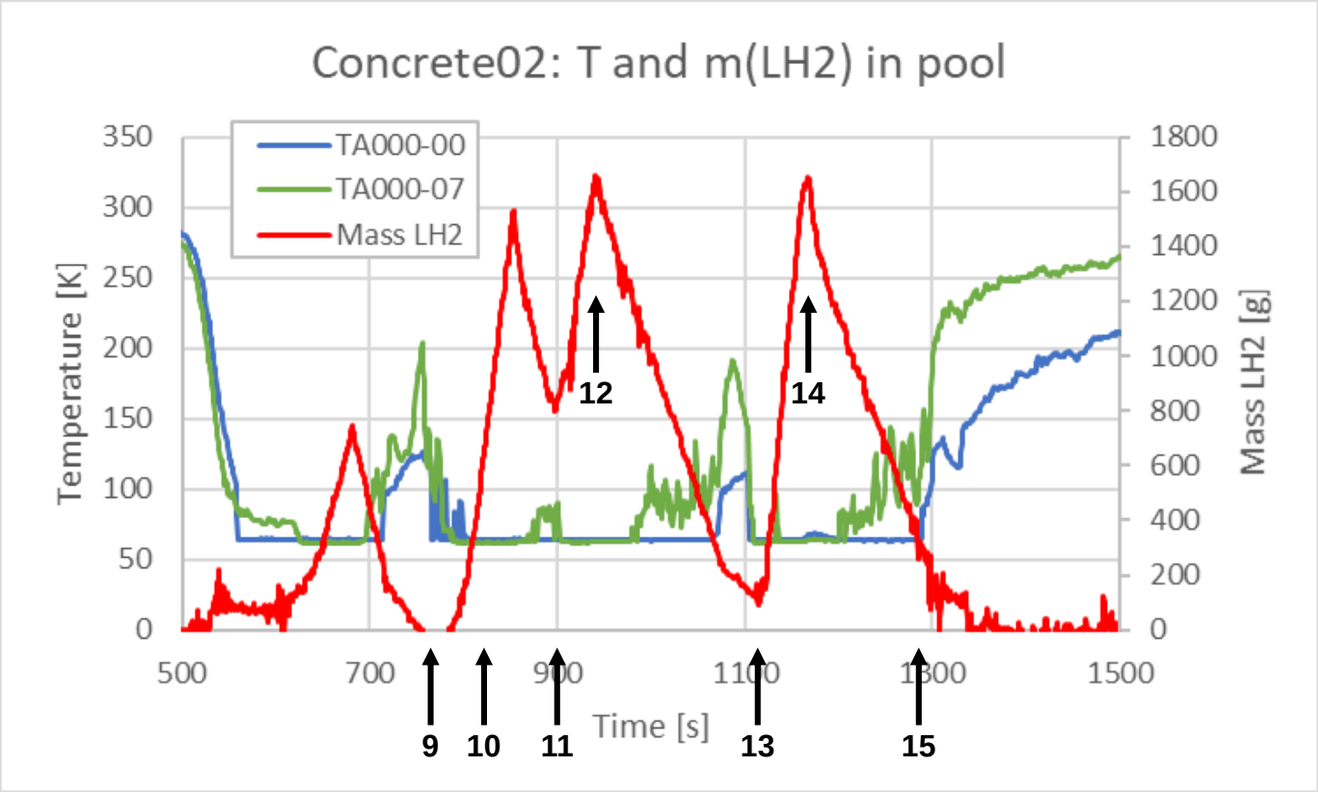


Pro-Science

E3.4 Unignited Pool Experiments

Experiment Concrete Pool02

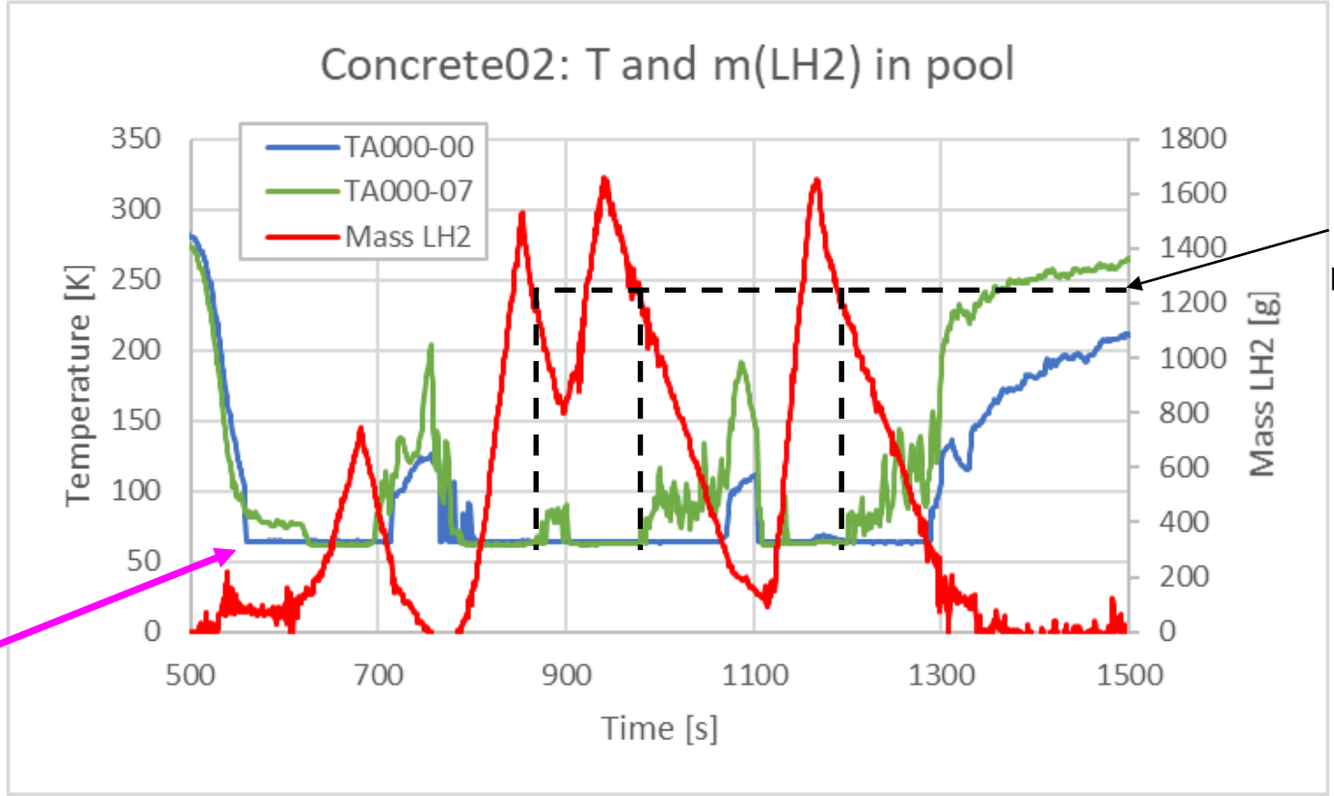
- **Measured temperatures in Concrete Pool and LH2 masses (II)**
  Graph shows temperature at substrate surface (T00, blue) and 7 cm above surface (T07, green) and LH2-mass (Mass, red),
  10. Pre-cooled substrate allows fast filling of pool almost up to upper rim,
  11. After LH2 had fallen below 7 cm release was re-started,
  12. Upper rim reached, LH2 release stopped,
  13. Pool almost evaporated, LH2 release re-started,
  14. Upper rim reached again, LH2 release stopped,
  15. Pool almost evaporated (increase in T00), further evaporation in gaps between concrete and pool wall and insulation.



E3.4 Unignited Pool Experiments

Experiment Concrete Pool02

- **Measured temperatures in Concrete Pool and LH2 masses (IV)**
  Correlation between LH2-mass and LH2-filling level
  - Pool height is $h_{pool} = m_{LH2}/(\rho_{LH2} \cdot L^2)$ with $\rho_{LH2} = 70.79$ kg/m³; L = 0.5 m
  - LH2 mass for 0,07 m pool height (= position of TA000-07) is 1.238 g,



LH2 mass for 7 cm pool depth

Temperature of LH2 measured by all TCs in Pool-experiments was approx. 63 K (+/- 2 K)

E3.4 Unignited Pool Experiments

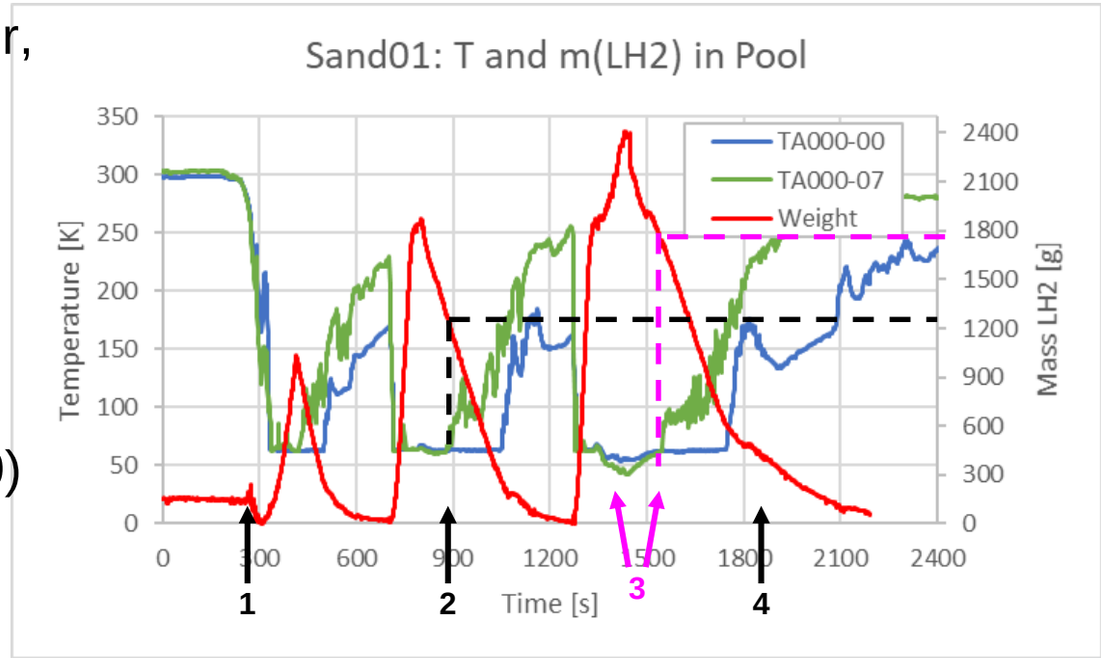
Experiment Sand Pool01

- **Measured temperatures in Sand Pool and LH2 masses**

  In principle same behavior, but…

  1. Initial weight reduction due to sand being blown out of the pool by gaseous H2,
  2. Filling level corresponds well with mass in second filling,
  3. But in third filling things change dramatically since pool is massively overflowing:
     - Weight increases above earlier maximum value
     - TCs show “lower than LH2 temperatures”
     - Filling level & mass correlate no longer,

     Reasons:
     - Gaps between pool and isolation are filled with LH2,
     - due to overflowing LH2 connectors of pool-TCs (outside on isolation) are exposed to droplets of LH2,
  4. After pool evaporation (increase in T00) long and slow mass reduction by approx. 500 g due to LH2 in gaps (Δm is approx. equal to higher maximum).

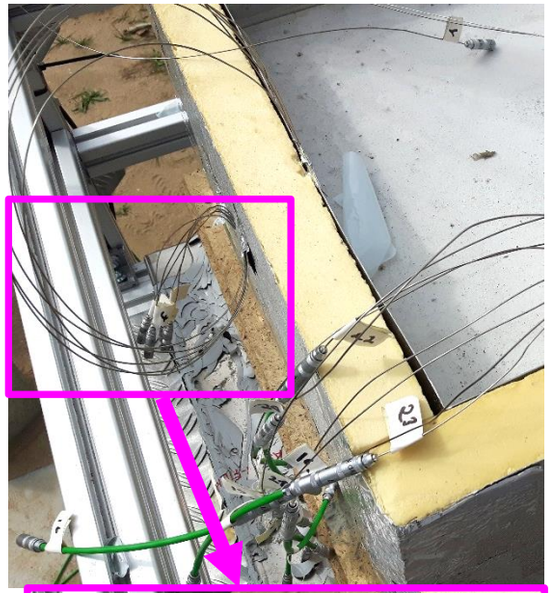


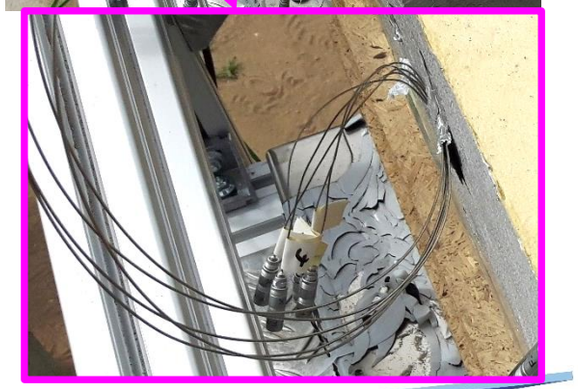
E3.4 Unignited Pool Experiments

Experiment Sand Pool01

- **Images to explain statements of previous slide**

  1. Initial weight reduction due to sand being blown out of the pool by gaseous H2,





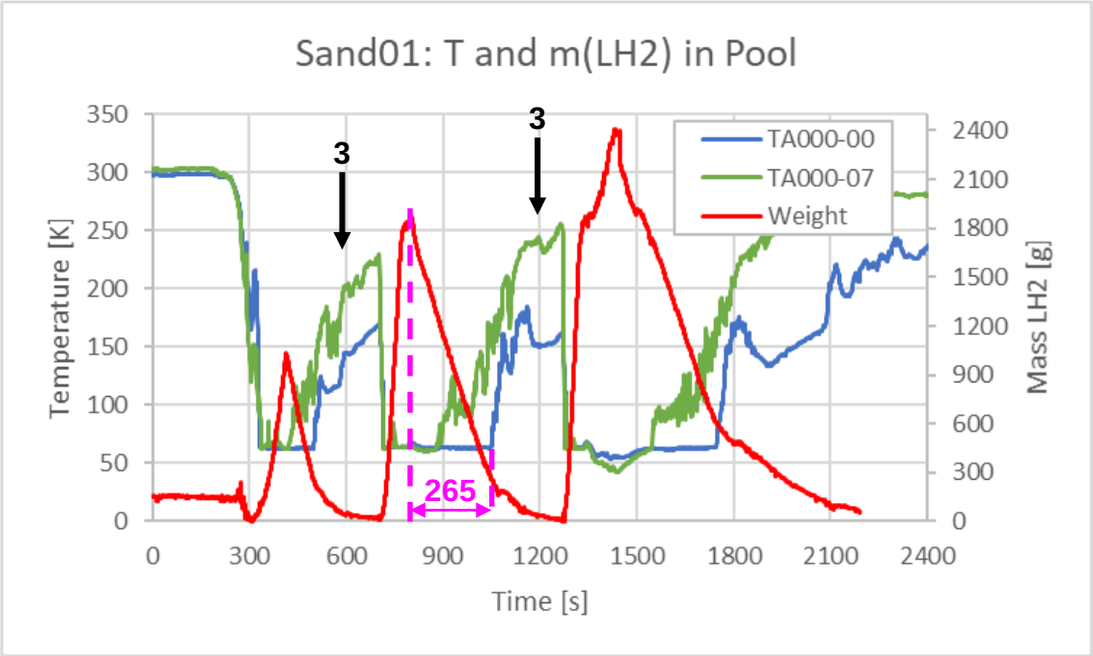
  3. Gaps between pool and isolation are filled with LH2, and
     connectors of pool-TCs (outside on isolation) are exposed to droplets of LH2.

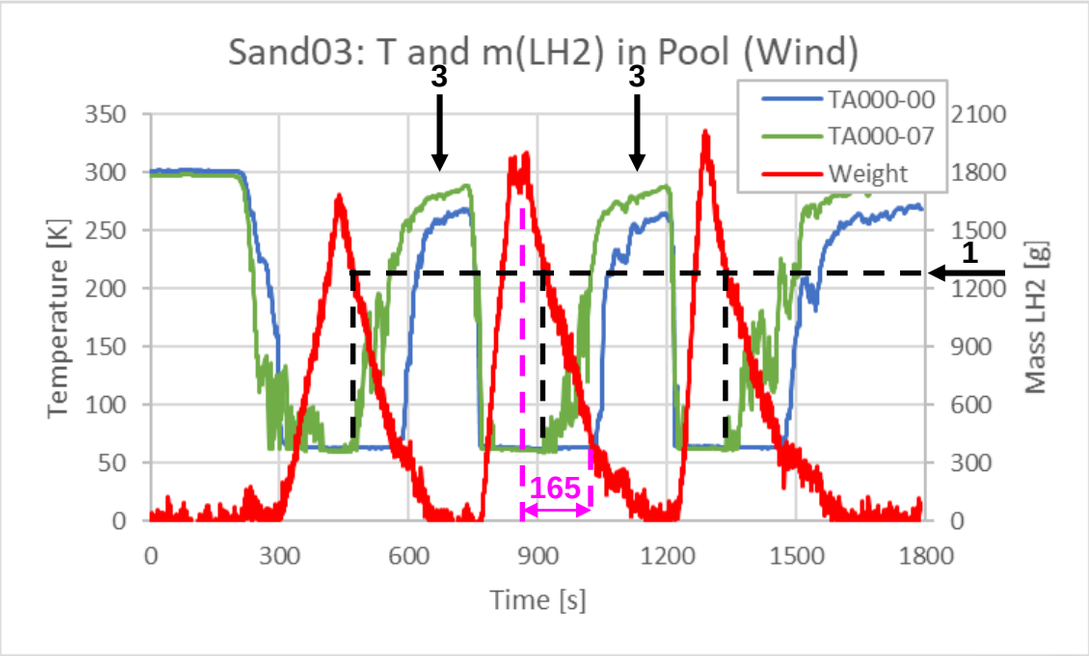
As soon as reasons were identified gaps were sealed and connectors were protected

E3.4 Unignited Pool Experiments

Experiment Sand Pool03 with “artificial wind”

- **Measured temperatures in Pool and LH2 masses**
  Wind velocity (≈ 5 m/s) measured separately with anemometer in same distance as pool center.
  1. Filling levels correspond with mass and no “lower-than-LH2-temperatures” (no overflow),
  2. Formation of second pool similar (65 s versus 75 s) but
     Evaporation time (until increase in T0) significantly lower with wind,
  3. Temperature increase after pool evaporation much faster and to much higher values.

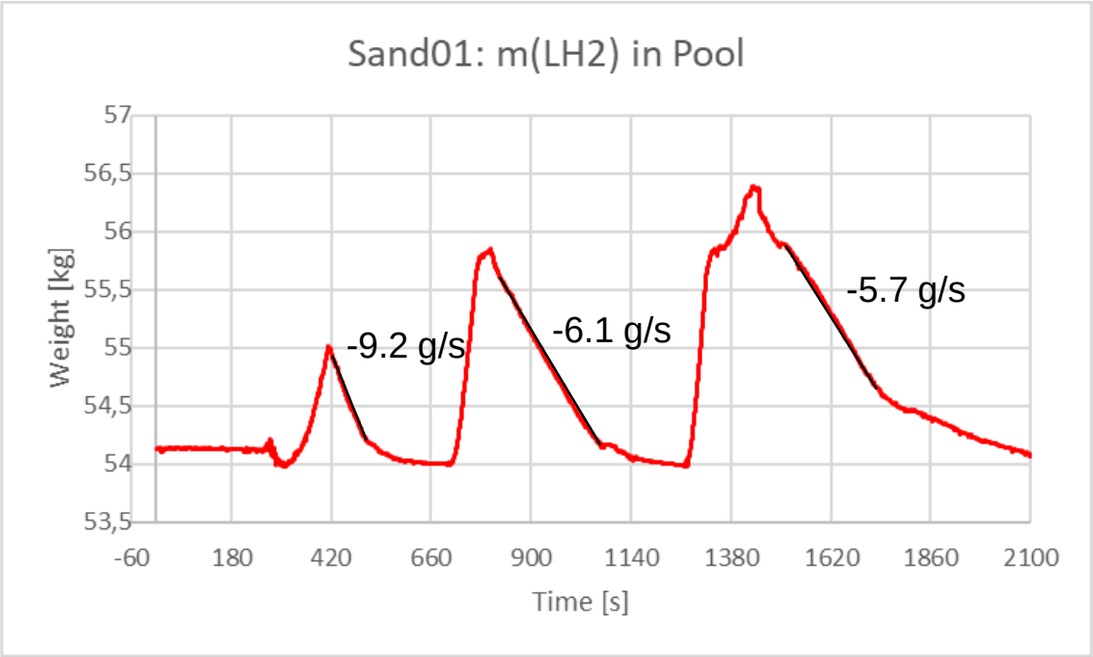


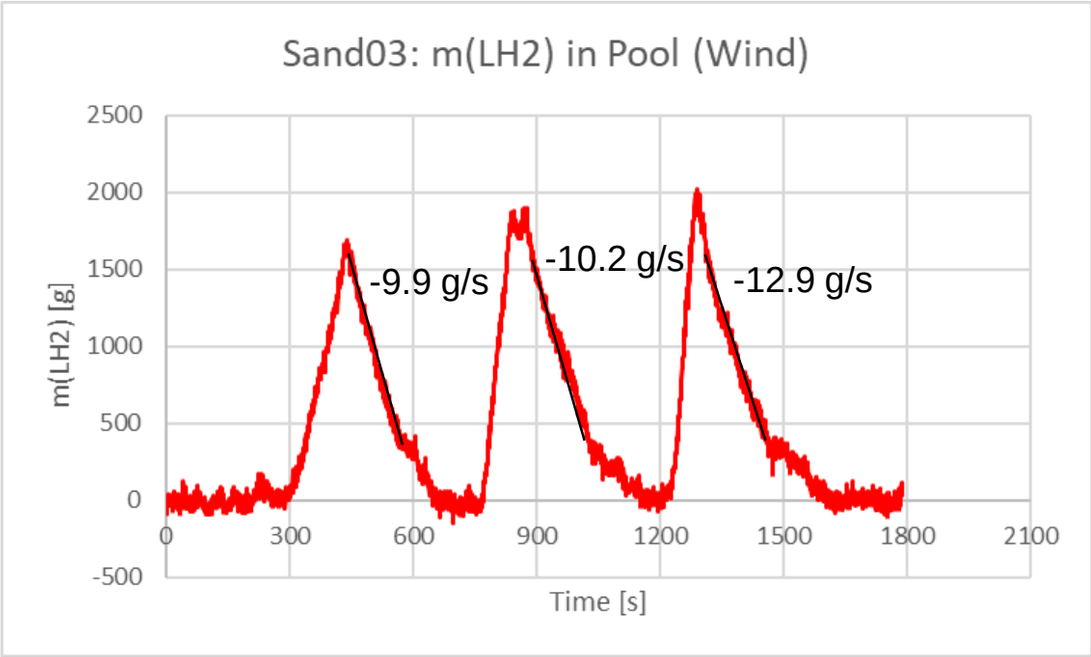


E3.4 Unignited Pool Experiments

Experiment Concrete Pool02

- **Measured LH2 masses in Sand Pools**
  Correlation between LH2-mass and LH2-Evaporation rate
  - Weight decrease after end of filling can be used to determine evaporation rate of LH2 in pools over different substrates,
  - Evaporation rates with wind significantly higher in experiments with artificial wind.





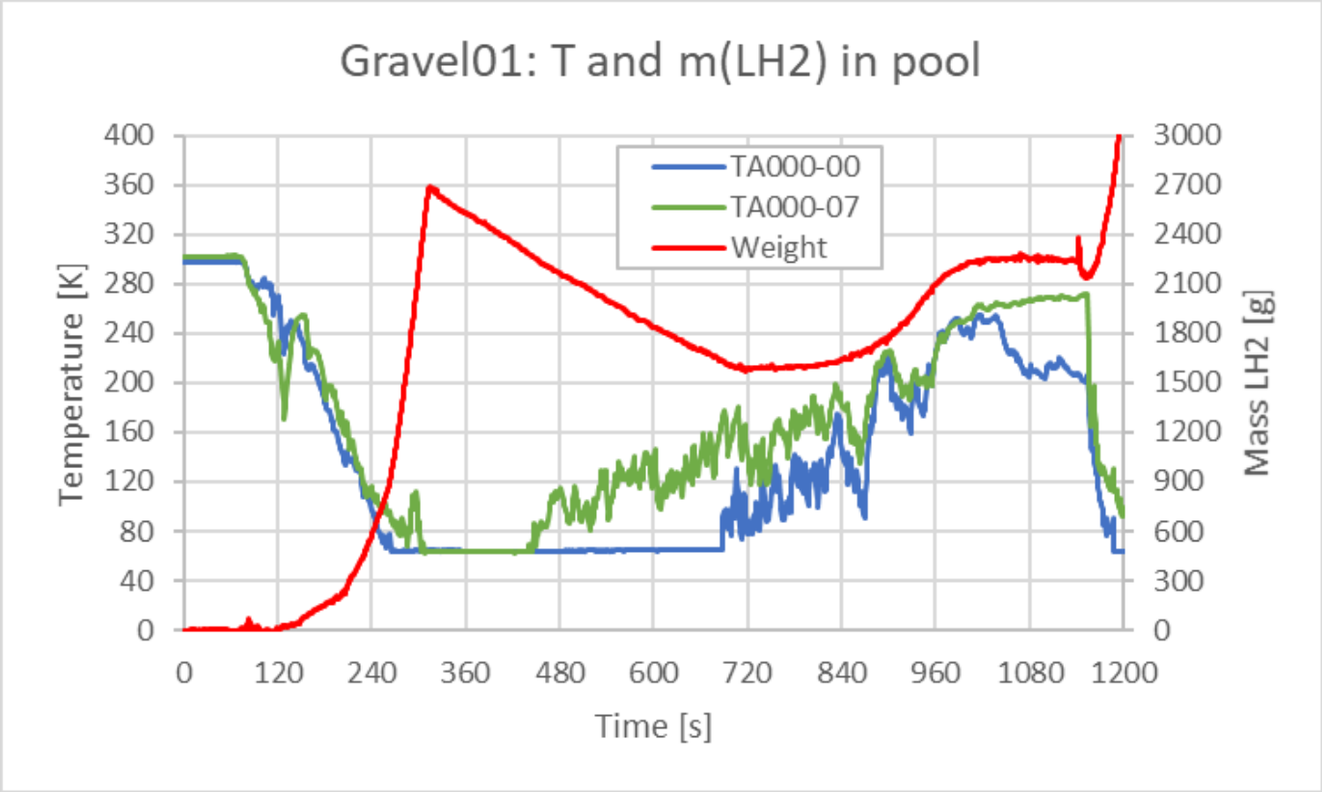
E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

- **Measured temperatures in Pool and LH2 masses (I)**

  Gravel-Experiments had quite long duration, so curves are discussed stepwise

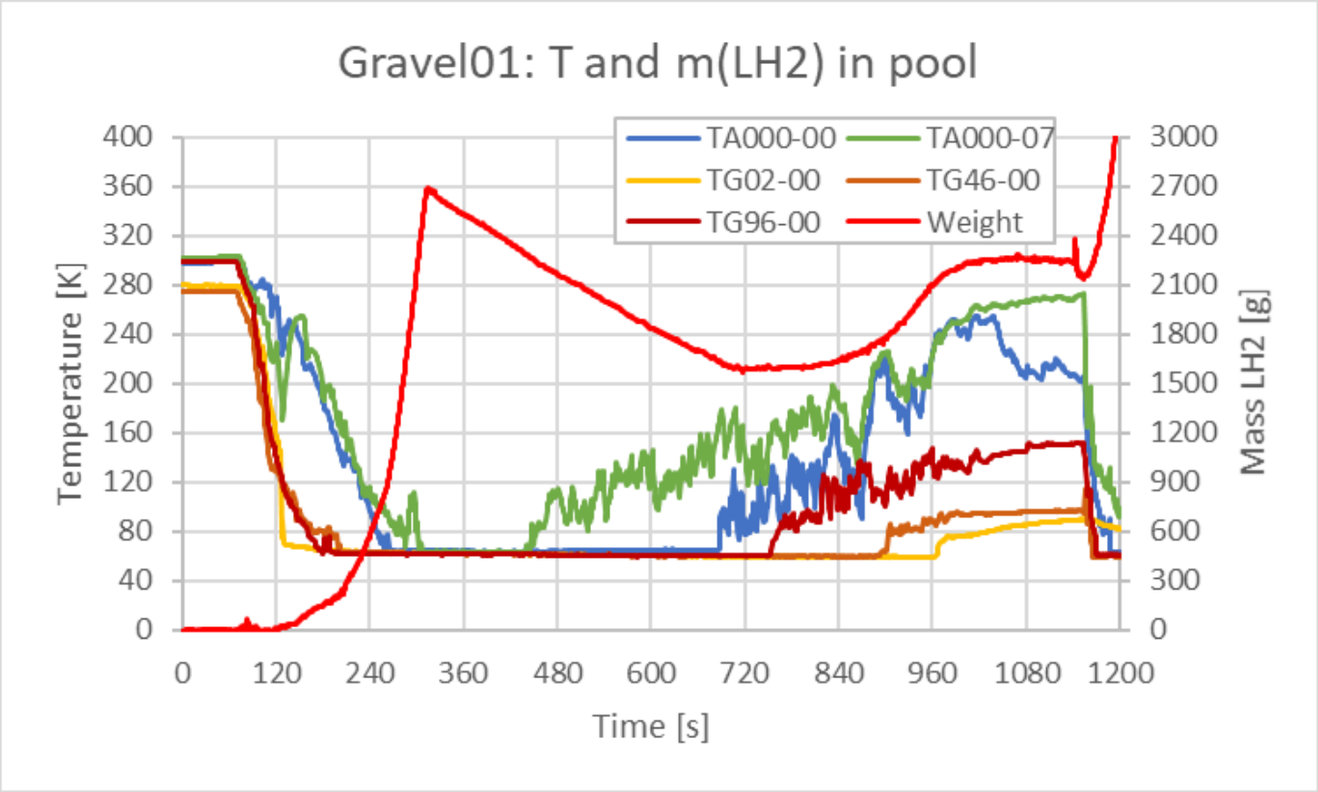
  1. Duration of initial filling (≈ 200 s) is longer than for other substrates and leads to much higher weight (≈ 2700 g compared to ≈ 1800 g in other tests (+50%)),
  2. In following evaporation weight loss much is slower than with other substrates and stops at a value of 1580 g (shortly after beginning of increase in T0),
  3. Thereafter weight increases more and more without further LH2 addition.



E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

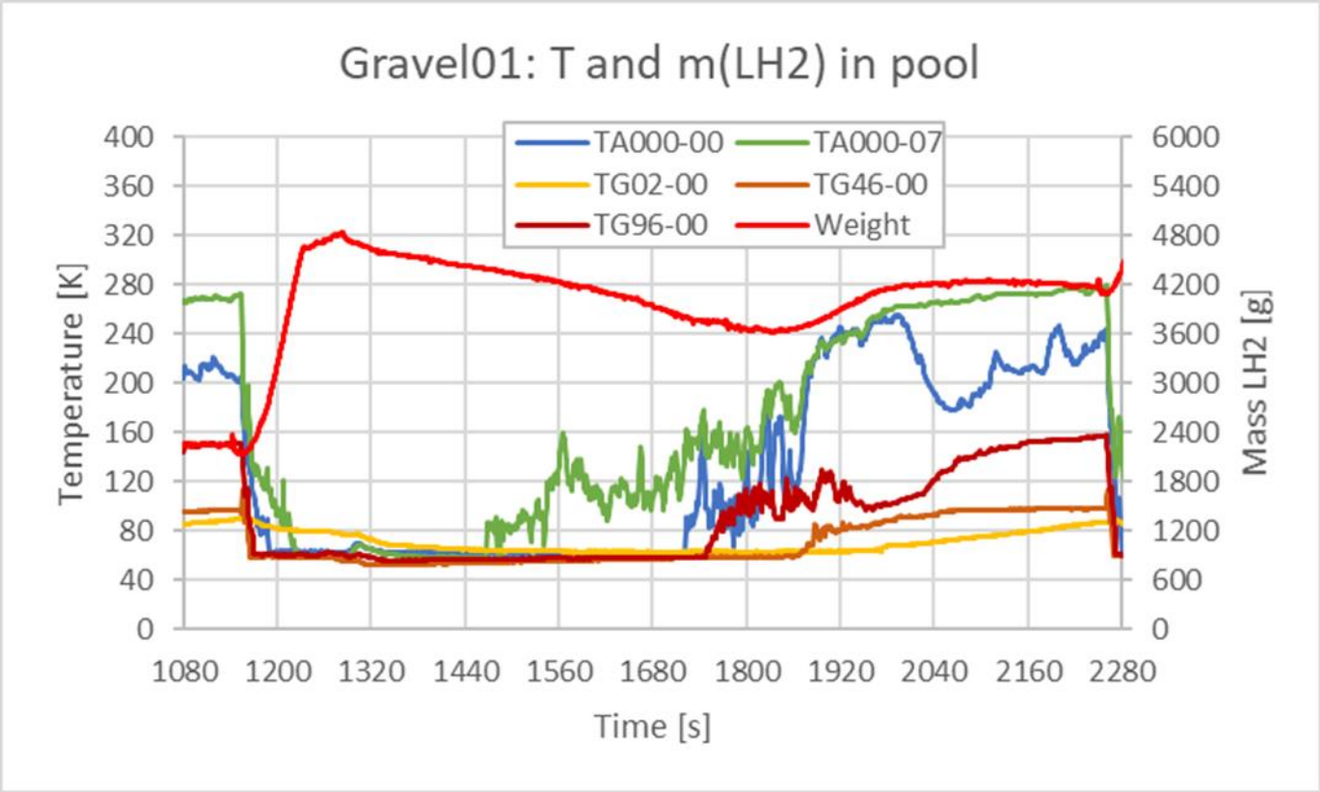
- **Measured temperatures in Pool and LH2 masses (II)**
  Temperatures in the substrate also reach LH2-level and thus:
  - The complete pool (except for volume occupied by gravel) was filled with LH2, (in densest packing of equal spheres 74% of space is occupied, but gravel used was not equal sized and not densely packed, so volume fraction of 50% for gravel seems reasonable),
  - After evaporation of pool cool substrate with large surface starts to condensate/freeze air (temperature in substrate at -54 mm approaches LN2-value of thermocouples (96 K))



E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

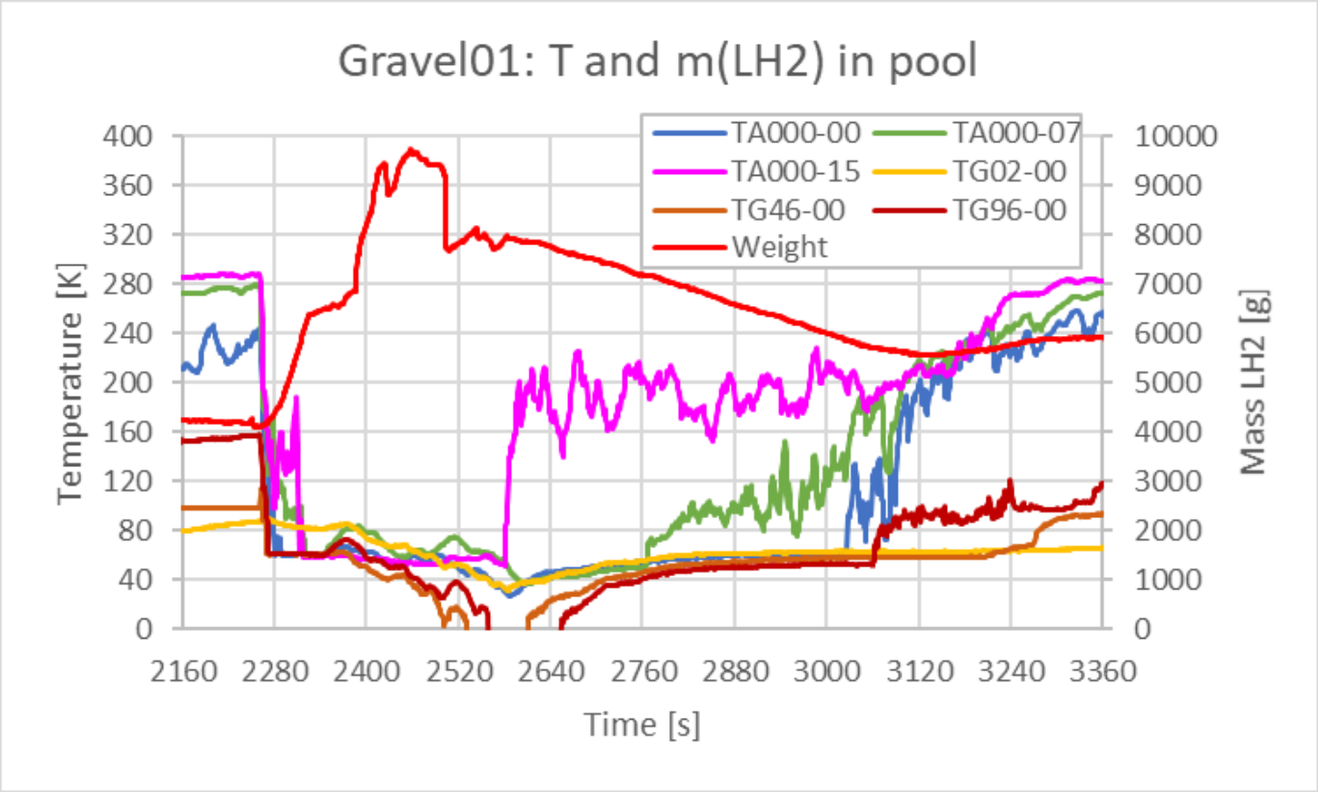
- **Measured temperatures in Pool and LH2 masses (III)**
  - Second filling starts at weight of 2160 g and further 2.6 kg were added until the LH2 release was stopped due to (slight) overflow of pool.
  - Following evaporation is again very slow and incomplete. Weight-value approaches 3600 g before again weight increase without LH2-addition starts,
  - Temperature in substrate at -54 mm again approaches LN2-value of thermocouples.



E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

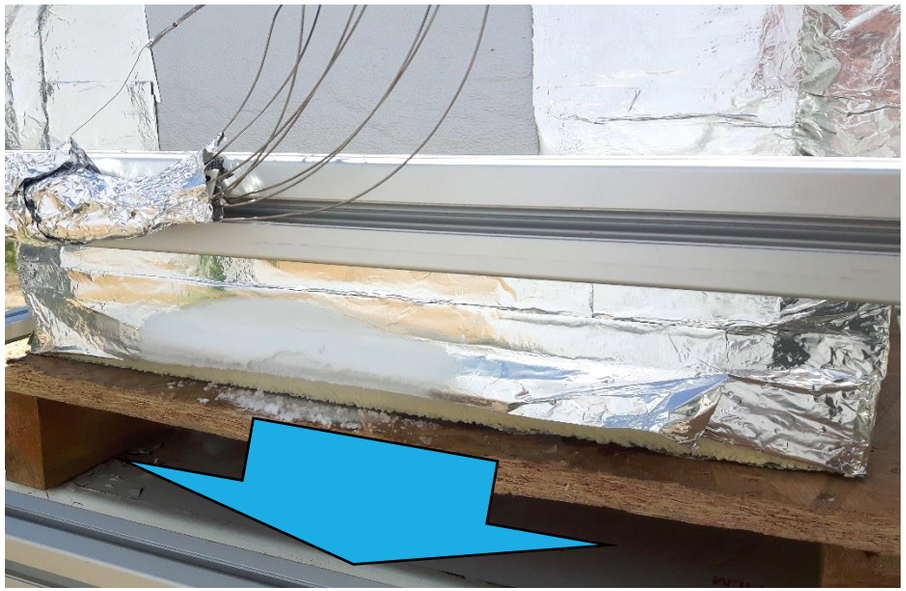
- **Measured temperatures in Pool and LH2 masses (IV)**
  - Third filling starts at weight of 4200 g and further 2 kg were added until weight increase slowed down before another strong increase to almost 10 kg ocured,
  - Reason seems to be massive overflowing ("lower-than-LH2-temperatures" at pool TCs) at t ≈ 2400 s with filling of gaps.
  - Then suddenly, before release was stopped, weight strongly decreases at t ≈ 2500 s,
  - Thereafter (t ≈ 2575 s) LH2-release was stopped, as record of TA15 (5 cm above upper pool rim) indicates,
  - Then weight decreases slowly to 5.5 kg before again slight increase occurs.

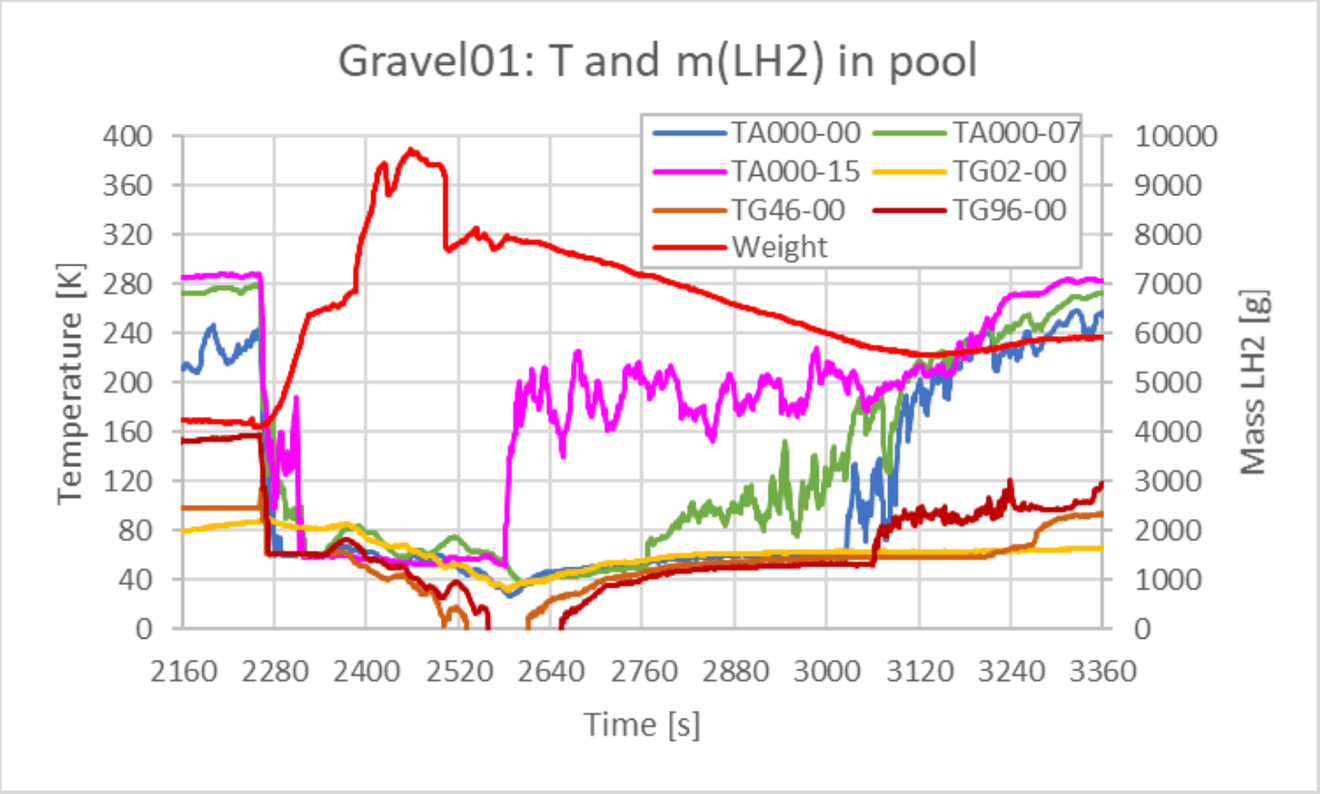


E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

- **Measured temperatures in Pool and LH2 masses (V)**
  - Reason for sudden weight decrease at t ≈ 2500 s seems to be rupture in insulation (as also observed in other tests).

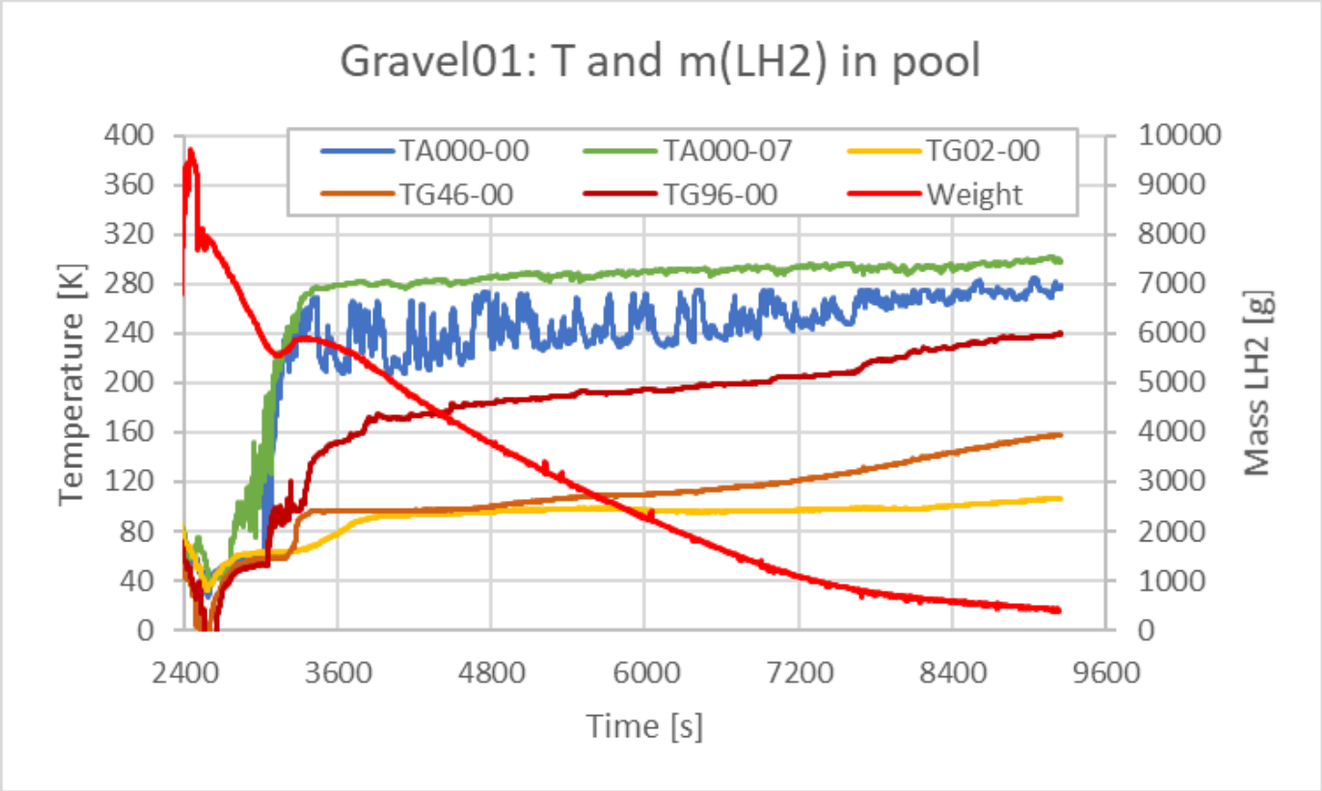




E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

- **Measured temperatures in Gravel Pool and LH2 masses (VI)**
  - After release was stopped (t ≈ 2580 s) weight decreases very slowly from an inventory of almost 6 kg to a value below 1 kg during more than one hour,
  - Temperatures in substrate indicate that liquid air has accumulated in unblocked volume of pool,
  - When pool was approached no H2 could be detected with H2-sensors, but a crackling sound was heard,
  - In later repetitions of this experiment (Gravel02 and 03) gas samples from within the stone rubble were taken and analyzed later.



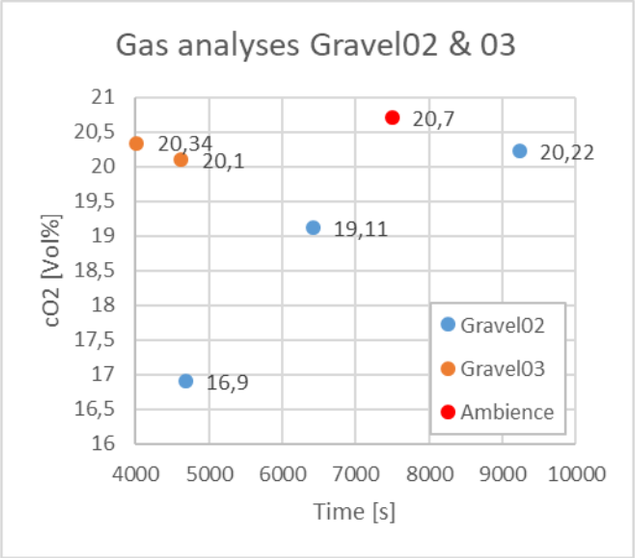
E3.4 Unignited Pool Experiments

Experiment Gravel Pool01

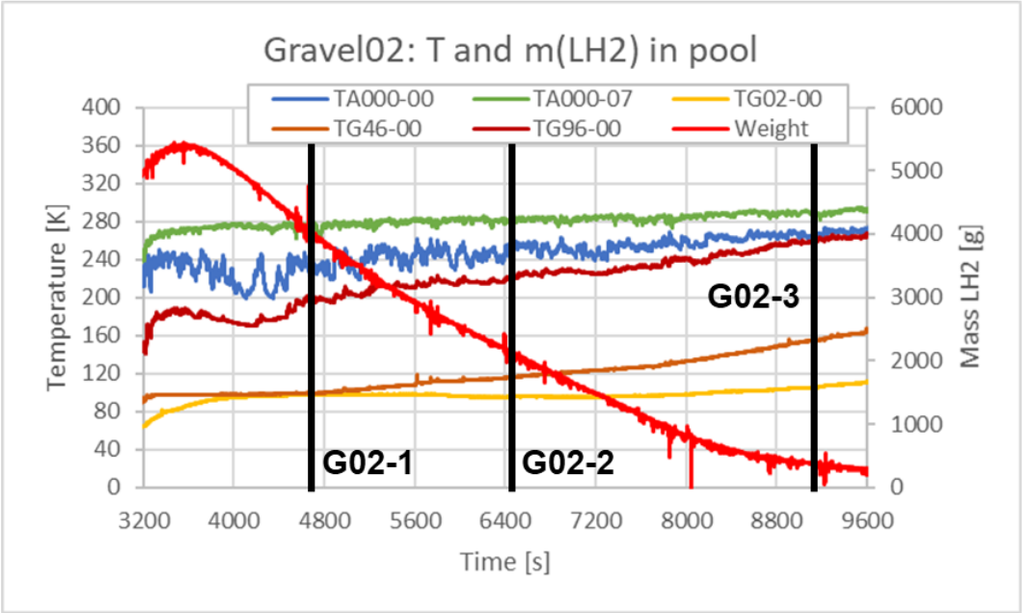
- **Remark to Gravel Pool 01**
  - After the experiment the facility was inspected and a victim of the test was found,
  - A flying insect was captured by the pool, potential ignition source?
    (organic material potentially coming into contact with liquid oxygen)

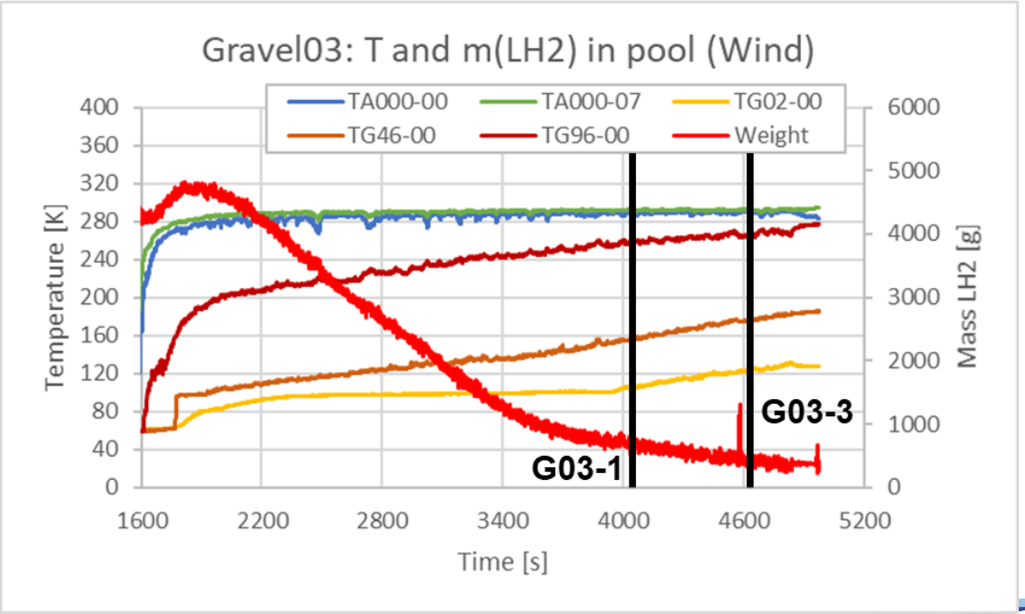
E3.4 Unignited Pool Experiments

Experiment with Gravel Pools



- **Gas analyses in Gravel02 and Gravel03(Wind)**
  - Only analyses on oxygen were possible,
  - Samples of Gravel02 show rather oxygen depletion than enrichment in substrate (compared to ambient air),
  - Second sample taking cylinder for Gravel03 defective (so ambient air was analyzed)
  - In experiment with wind (Gravel03) no very low O2-depletion was found.





Ignited Pool-Experiments (WP4.4)

A. Friedrich, A. Veser, G. Necker, J. Gerstner,

N. Kotchourko

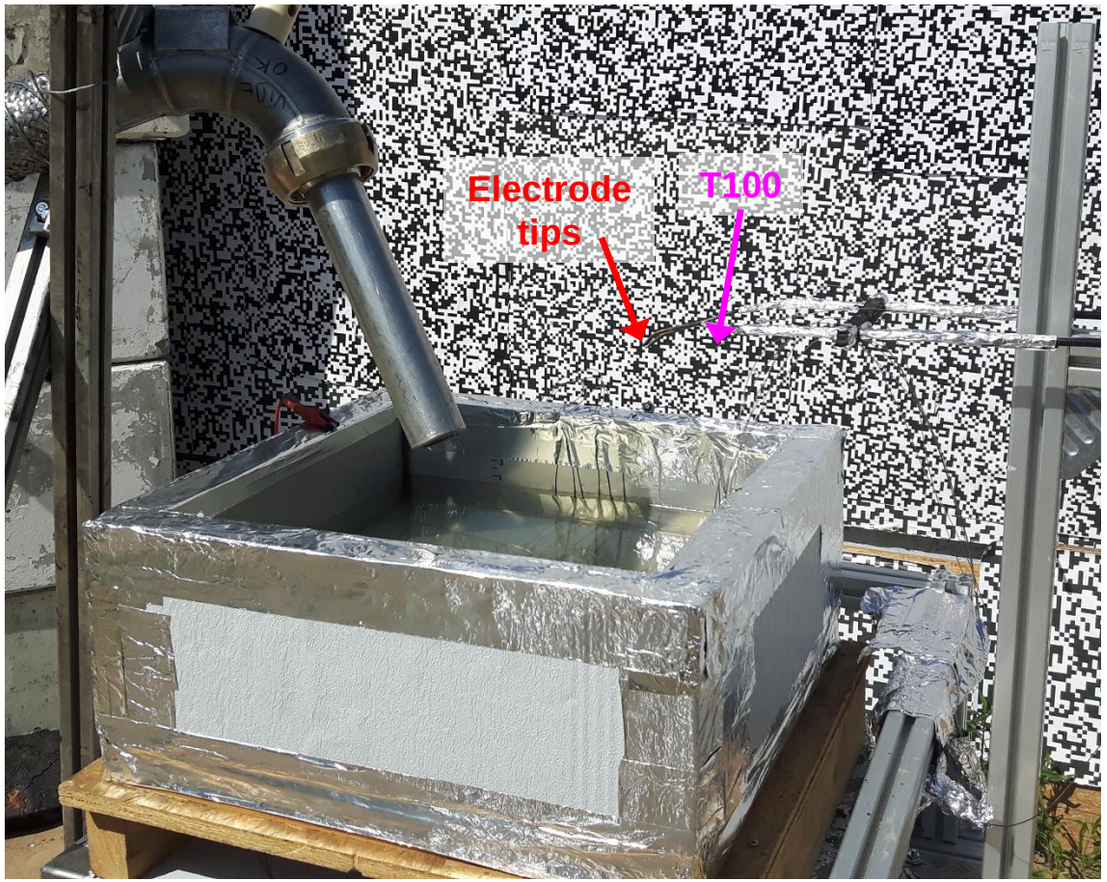
July 30st 2020

Pre-normative REsearch for Safe use of Liquid HYdrogen

E4.4 Ignited Pool Experiments

Specific instrumentation ignited Pool-Experiments

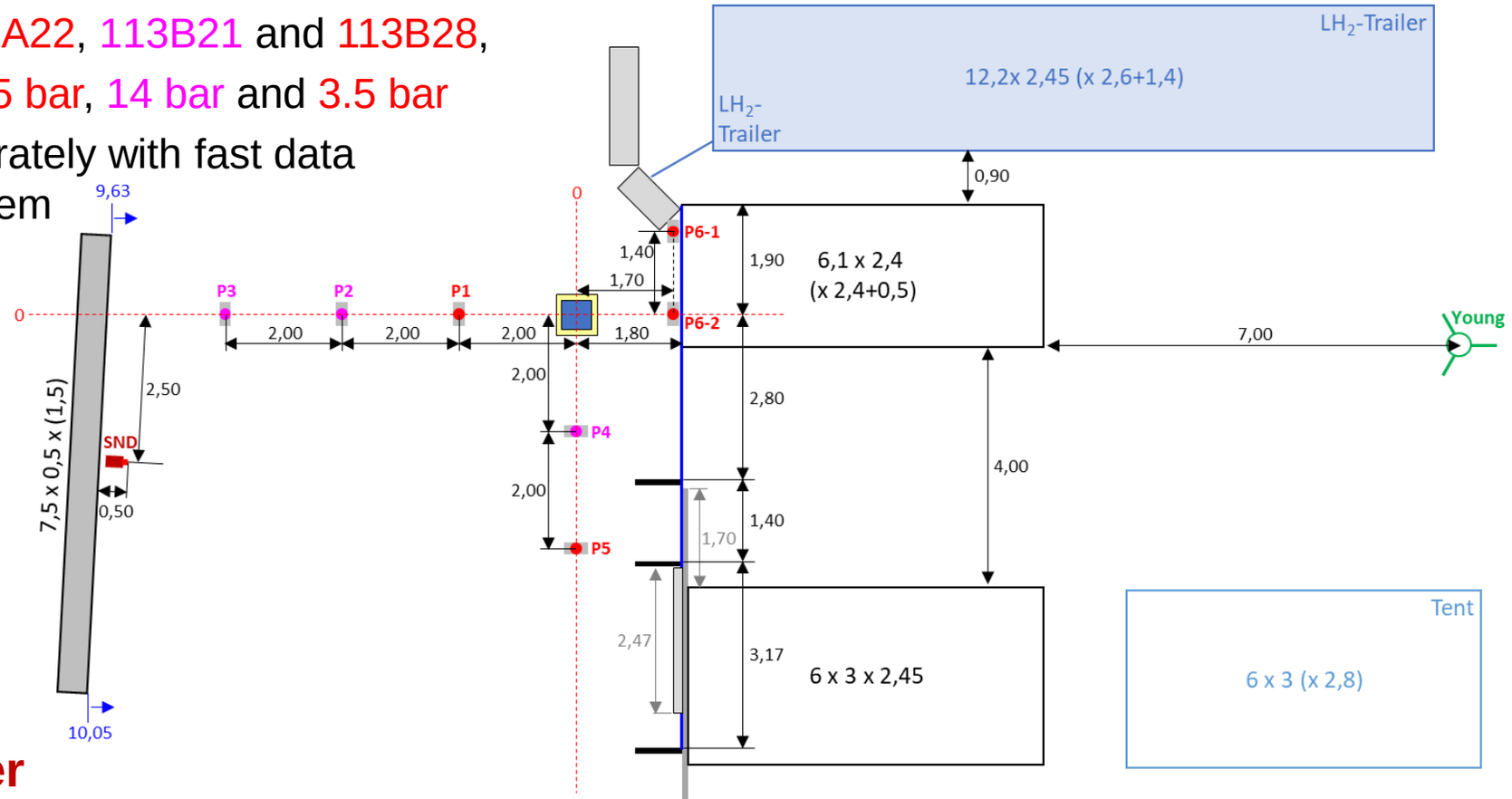
- **Ignition electrodes**
  - Electrode diameter: d = 3.5 mm,
  - pointed tips,
  - Gap size ≈ 4 mm,
  - Output: 20 kV / 60 kHz,
  - Ignition duration: 1 s
  - Ignition position 10 cm off the pool center (15 cm from pool wall) in different heights,
  - For second (Sand05) and all following ignition experiments thermocouple T100 was installed close to the ignition electrodes to monitor performance and point in time of the ignition.



E4.4 Ignited Pool Experiments

Specific instrumentation ignited Pool-Experiments

- **Fast dynamic pressure sensors**
  - PCB types: 112A22, 113B21 and 113B28,
  - Sensitivities: 3.5 bar, 14 bar and 3.5 bar
  - Recorded separately with fast data acquisition system



- **Sound level meter**
  - Type: roline RO1350
  - Distance: d ≈ 8 m

- **Anemometer (ambient wind conditions)**
  - Type: YOUNG model 81000,
  - Wind in 3 directions (N→S, E→W, ↑ Up) and T.

E4.4 Ignited Pool Experiments

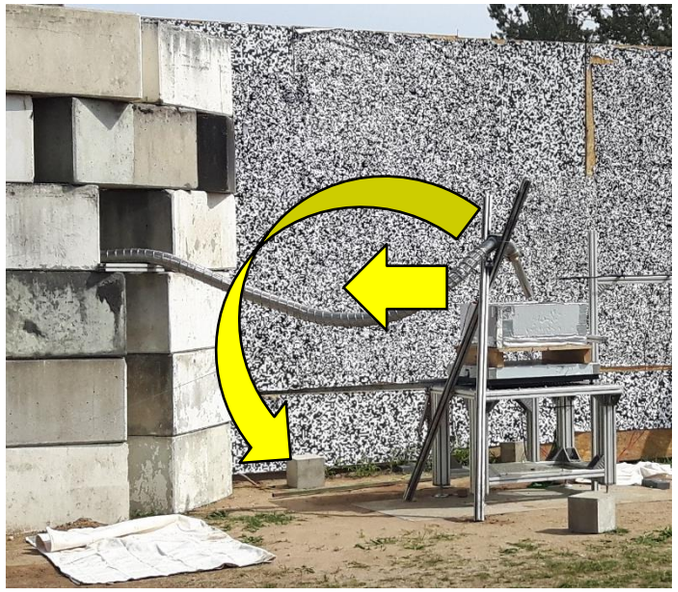
Test Matrix

- **Ignited Pool Experiments (E4.4)**
  - In total 14 ignited experiments were performed with the Pool-facility,
  - Experiments performed with all four substrates (concrete, sand, gravel, water),
  - Main variable apart from substrate was ignition height.

Date	Substrate	Procedure	Ignition Height [cm]	Comments
24.04.2020	**Sand04**	2 Fillings	25	
24.04.2020	**Sand05**	2 Fillings	25	T100 moved close to ignition
24.04.2020	**Sand06**	2 Fillings	15	
27.04.2020	**Sand07**	2 Fillings	45	No ignition
27.04.2020	**Sand08**	2 Fillings	40	
27.04.2020	**Sand09**	2 Fillings	35	
27.04.2020	**Sand10**	2 Fillings	8	
27.04.2020	**Sand11**	2 Fillings	45	Repetition of Sand 07
27.04.2020	**Concrete04**	2 Fillings	45	
27.04.2020	**Concrete04**	2 Fillings	25	
27.04.2020	**Concrete04**	2 Fillings	15	
27.04.2020	**Concrete04**	2 Fillings	8	Ignition in 3rd attempt
27.04.2020	**Water02**	2 Fillings	25	
04.05.2020	**Gravel04**	2 Fillings	25	

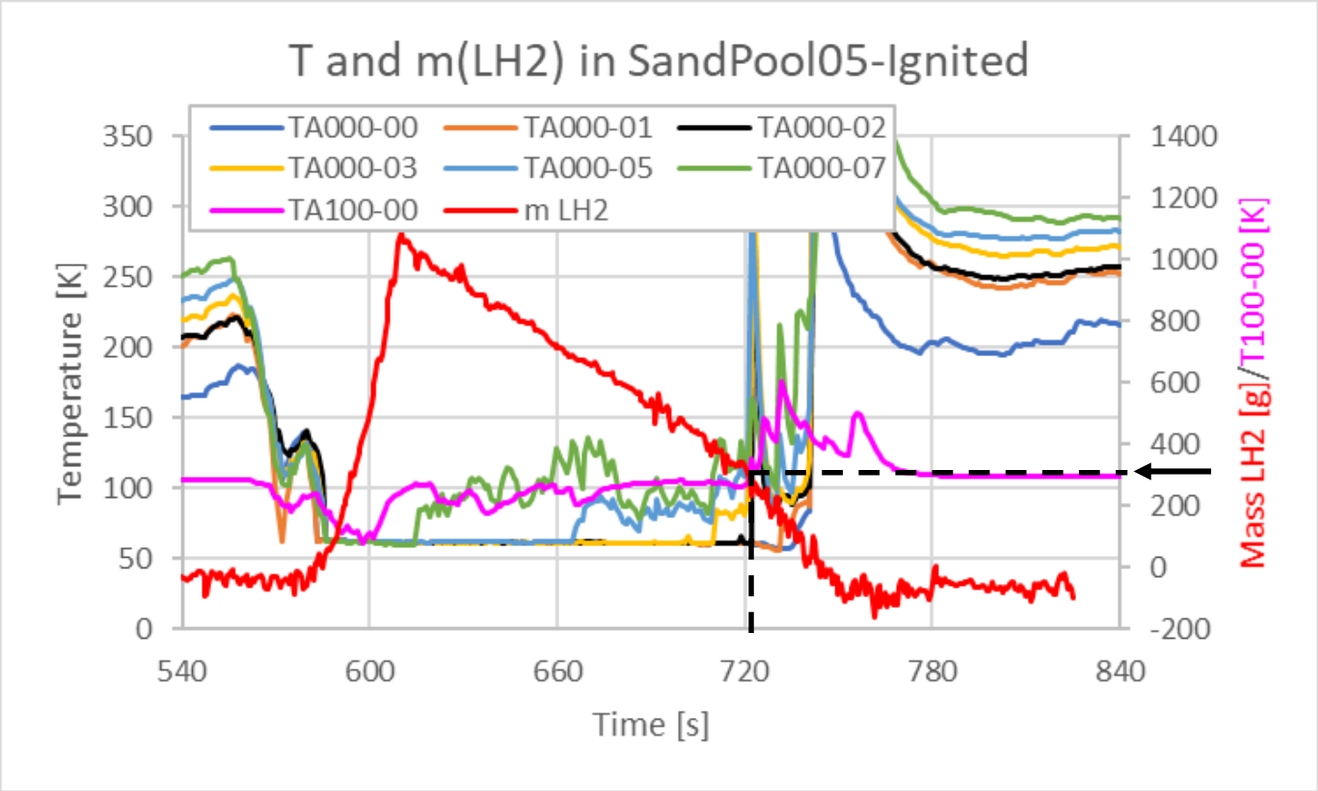
E4.4 Ignited Pool Experiments

- **Test procedure Ignited Pool Experiments**
  - Hose was positioned and fixed above pool,
  - Data acquisition (LabView) was started manually and then controlled remotely until end of experiment, cameras were started manually,
  - LH2-release was started manually (always to approx. the same degree of valve opening) at trailer but stopped remotely,
  - When 1st pool had evaporated 2nd release was again started manually (after safety check with hand held H2-sensor) and stopped remotely,
  - Fast data acquisition was started prior to every LH2-release initiation (waiting for trigger),
  - After 2nd release was stopped hose was removed from pool using a rope,



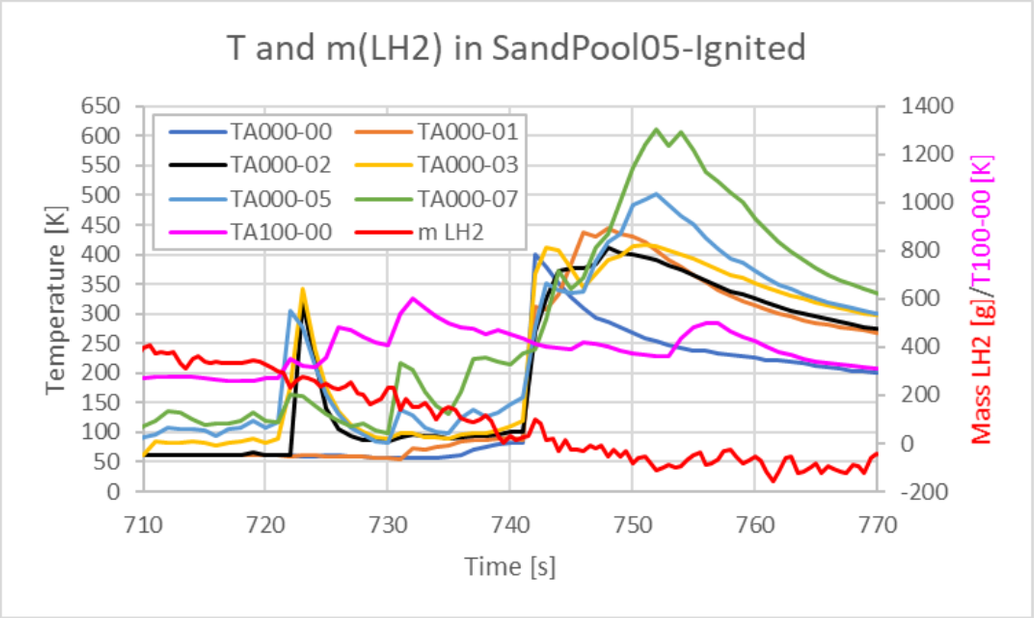
E4.4 Ignited Pool Experiments

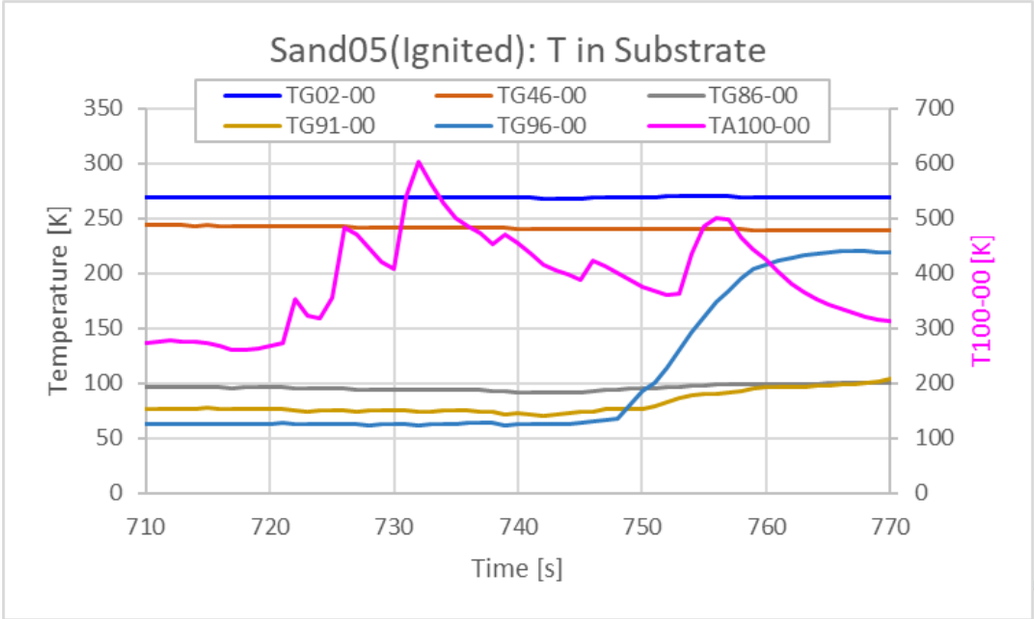
- **Test procedure - Ignited Pool Experiment Sand05**
  - After second filling LH2-level in pool was closely monitored,
  - Increase in temperatures indicates that respective thermocouple is no longer covered by LH2,
  - At a filling level of 3 cm (increase in **T03**) ignition was prepared, ignition was activated at filling level of 2 cm (increase in **T02**),
  - From second ignited experiment (Sand05) on thermocouple **T100** was positioned close to the electrodes to record moment of ignition,
  - According to the graph in experiment Sand05 an amount of approx. 300 g LH2 was in the pool in the moment of the ignition.



E4.4 Ignited Pool Experiments

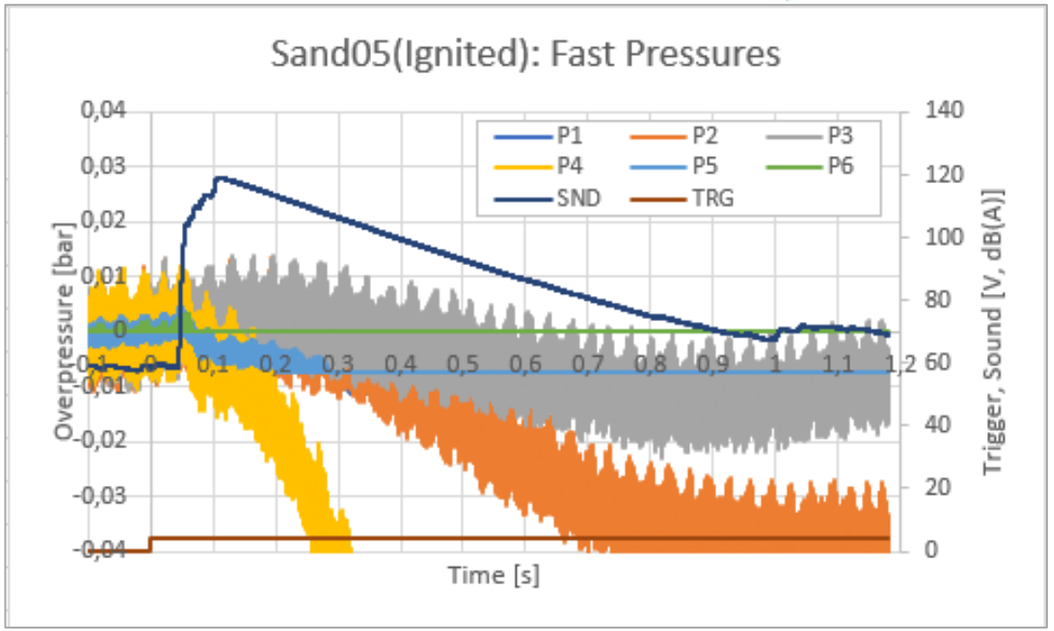
- **Ignited Pool Experiment Sand05**
  - After ignition initiation a first combustion event is detected by the TCs in the pool (t ≈ 722 – 727 s),
  - In a second combustion event only the uppermost TCs in the pool are reached (t ≈ 730 – 735 s),
  - and in the third combustion event the complete remaining inventory of the pool is burnt (t > 740 s).
  - Inside the substrate only the last combustion event leads to slight temperature increases of the two uppermost TCs in positions approx. 4 mm and 9 mm below the surface (TG96 and TG91).
  - The TCs above the pool were not installed in the ignited experiments.





E4.4 Ignited Pool Experiments

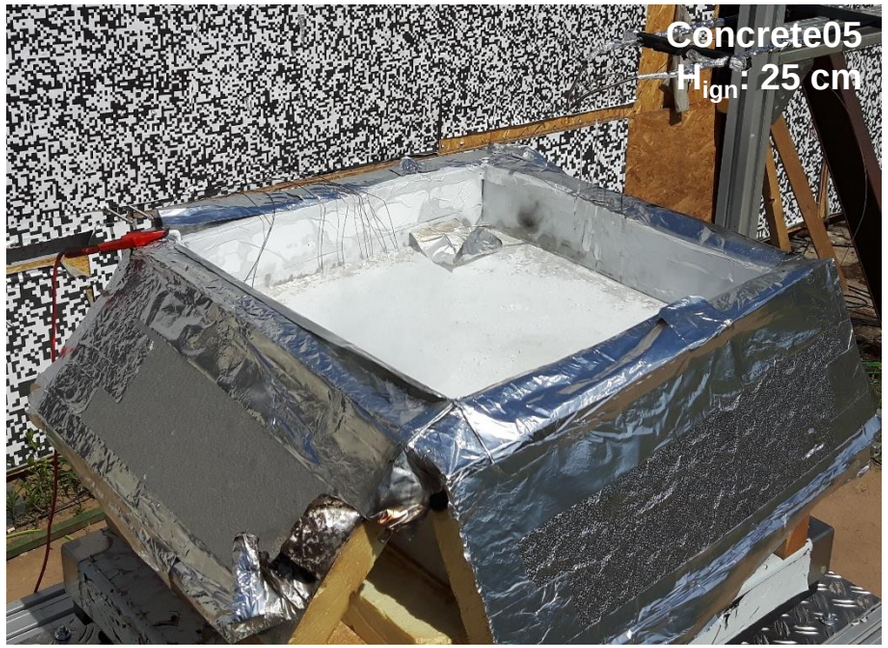
- **Ignited Pool Experiments Sand05**
  - No significant pressure increase recorded by fast pressure sensors since main combustion event occurred approx. 20 s after ignition was activated,
  - Difficult to find other criteria for triggering fast data acquisition since:
    - Impossible to predict point in time of main ignition event,
    - Pressure sensors are sensitive to temperature changes. In all previous unignited experiments data acquisition was triggered by temperature effects.
    - No chance to reactivate trigger when pool is filled due to safety restrictions (data acquisition in tent relatively close to pool).



E4.4 Ignited Pool Experiments

- **Ignited Pool Experiments**
  - Different degrees of damage observed during the experiment series:

- Almost undamaged: minor burns (e.g. Water02)
- More severe damage: partly ripped off insulation (e.g. Sand11, Concrete05)

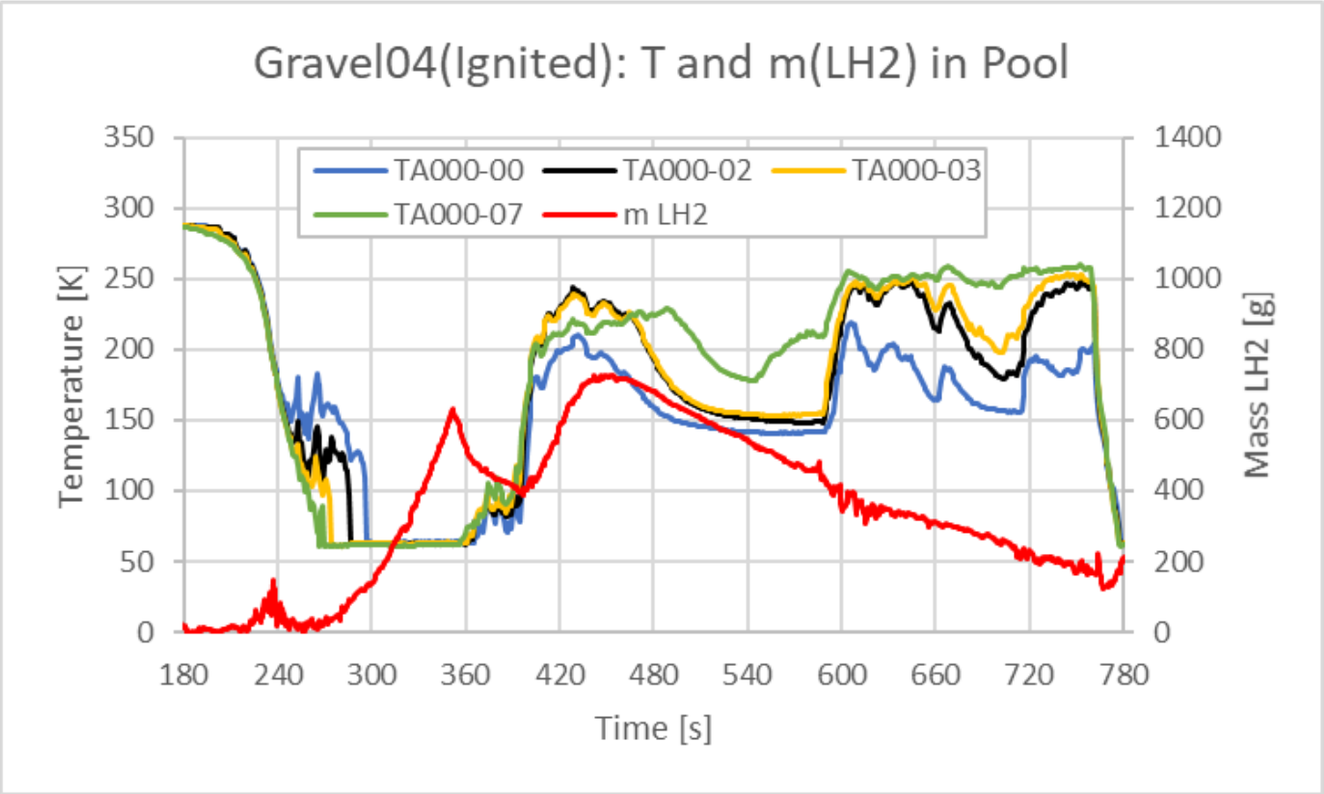


E4.4 Ignited Pool Experiments

- **Ignited Pool Experiments**
  - Different degrees of damage observed during the experiment series:
    - Complete destruction of the facility

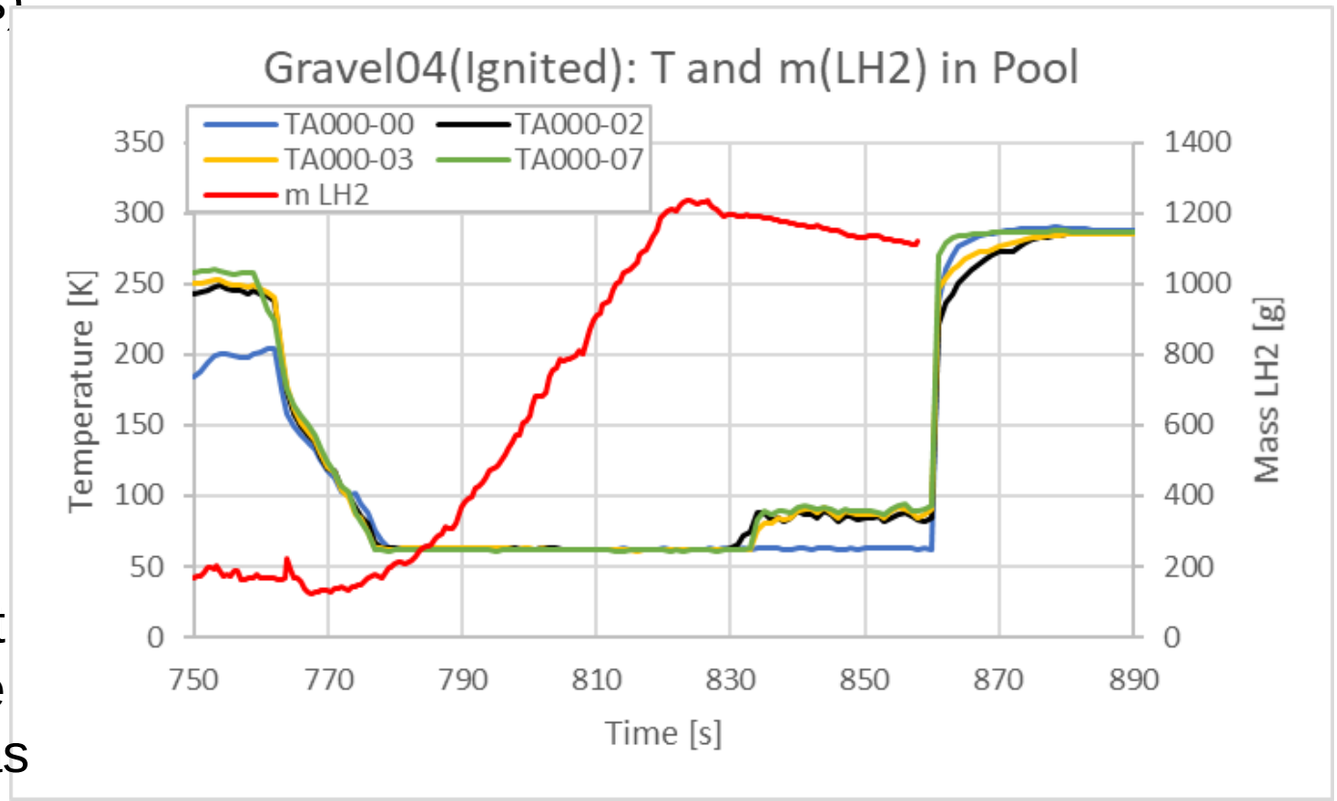
E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - Pool was refilled with gravel after experiment Water02, so pool was definitely water-tight in the beginning of this experiment,
  - 1st Filling procedure as usual: pool filled up to upper rim without significant overflow,
  - After end of 1st procedure LH2 evaporated and, when filling level had reached upper end of substrate, condensation/solidification of air started,
  - After t ≈ 450 s no further condensation but evapo-ration was observed, and at the beginning of the 2nd filling additional mass in pool was about 150 g.



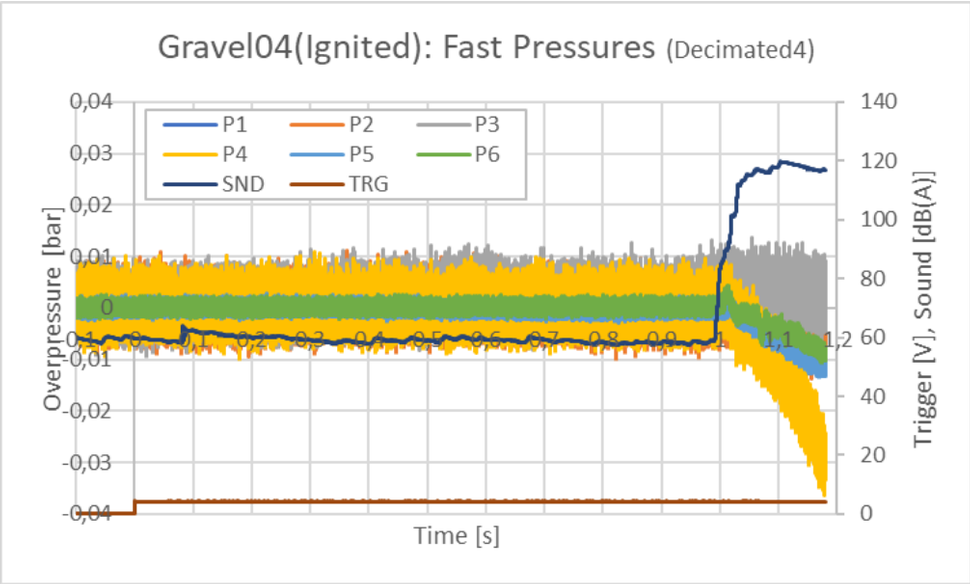
E4.4 Ignited Pool Experiments

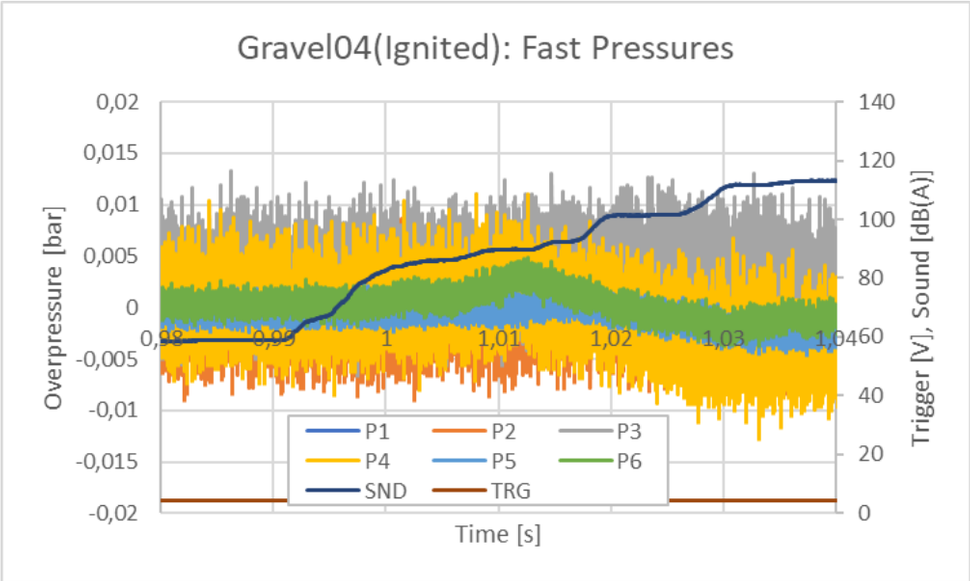
- **Ignited Pool Experiment Gravel04**
  - During 2nd filling procedure approx. 1100 g of LH2 were released into the pool until the release was stopped at t ≈ 825 s,
  - Already shortly after the end of the release all pool TCs except for T00 at the top level of the substrate show a temperature increase to a value of 82 - 92 K, (≈ 10 K > T_{LN2} of these TCs)
  - T00 and all TCs in the substrate measure a temperature around 63 K (≈ T_{LH2} of these TCs),
  - When the ignition was activated the additional mass in the pool was about 1100 g,
  - Only one combustion event visible in records where the complete cold inventory was removed from the pool.



E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - In this combustion event no significant pressure increase was recorded before the sensor signals start to decrease due to temperature effects,
  - The maximum sound level recorded (119,6 dB(A)) in a distance of 8 m indicates, that a major combustion event had at least started during the time span of the record.





E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - After the experiment the facility was completely destroyed and the also the cold gravel was removed from the pool and was scattered over a wide area on the free field test site,
  - Due to condensing humidity gravel pieces could be easily identified. So after the test the area was inspected and several stones were collected and their positions sketched and the distance to the pool was measured,
  - The heaviest stone (m = 267 g) was found in a distance of 15 m to the pool,
  - The stone found in the farthest distance to the pool (d ≈ 41 m) had a weight of 137 g,
  - Optical analyses of high-speed movies calculated stone-velocities of almost sound speed close to the pool.

E4.4 Ignited Pool Experiments

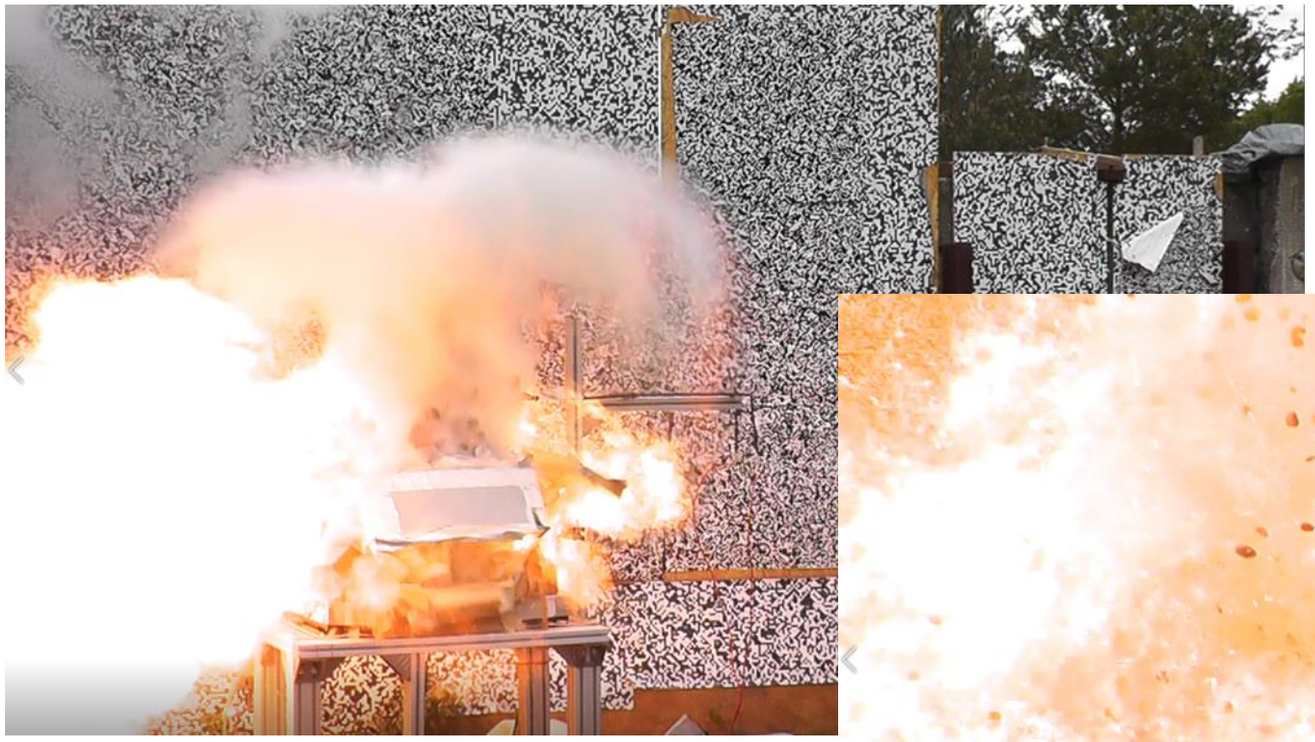
- **Ignited Pool Experiment Gravel04**
  - Photo observation (Canon 1, approx. 3 fps)

E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - Photo observation (Canon 2, approx. 4 fps)

E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - Video observation (Panasonic 1, 50 fps)



E4.4 Ignited Pool Experiments

- **Ignited Pool Experiment Gravel04**
  - Video observation (PHOTRON High-Speed Camera)

Thank you for your

Attention!