Large Volume Liquid Hydrogen Releases

Key results and outcome of modelling exercises

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* Presenting

Full Reports and Dataset:
https://www.vegvesen.no/fag/trafikk/ferje/utviklingskontrakt-hydrogen/testing/

Introduction

- Project executed by FFI Forsvarets forskningsinstitutt Norwegian Defence Research Establishment and relating to LH_2 bunkering
- Funding provided by Statens vegvesen (Norwegian Public Roads Administration)
- Need for large scale data on LH2 release phenomena for model development and validation
  - ‘Outdoor Releases’
    - Including preliminary modelling exercise (Ann and Jan)
  - ‘Closed Room Releases’
- Today:
  - Experimental Arrangements and methods used
  - Programme Details
  - Results by phenomenon
  - Introduction to modelling

DNV

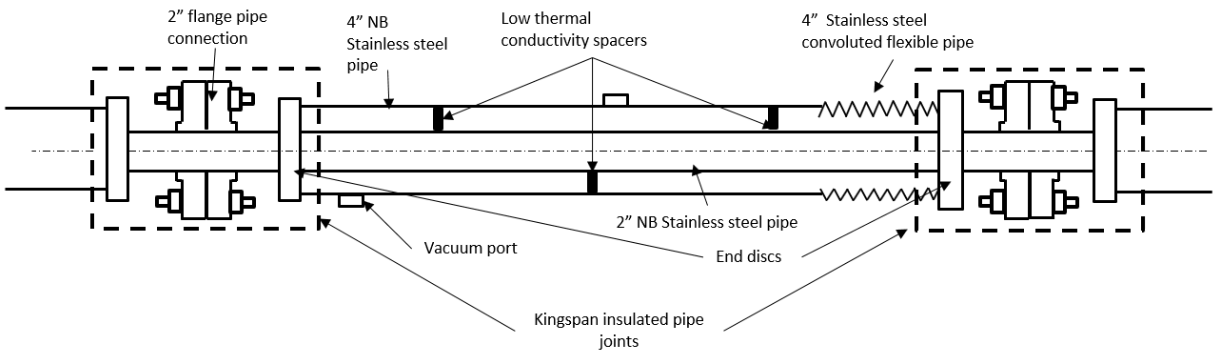
Experimental Arrangement

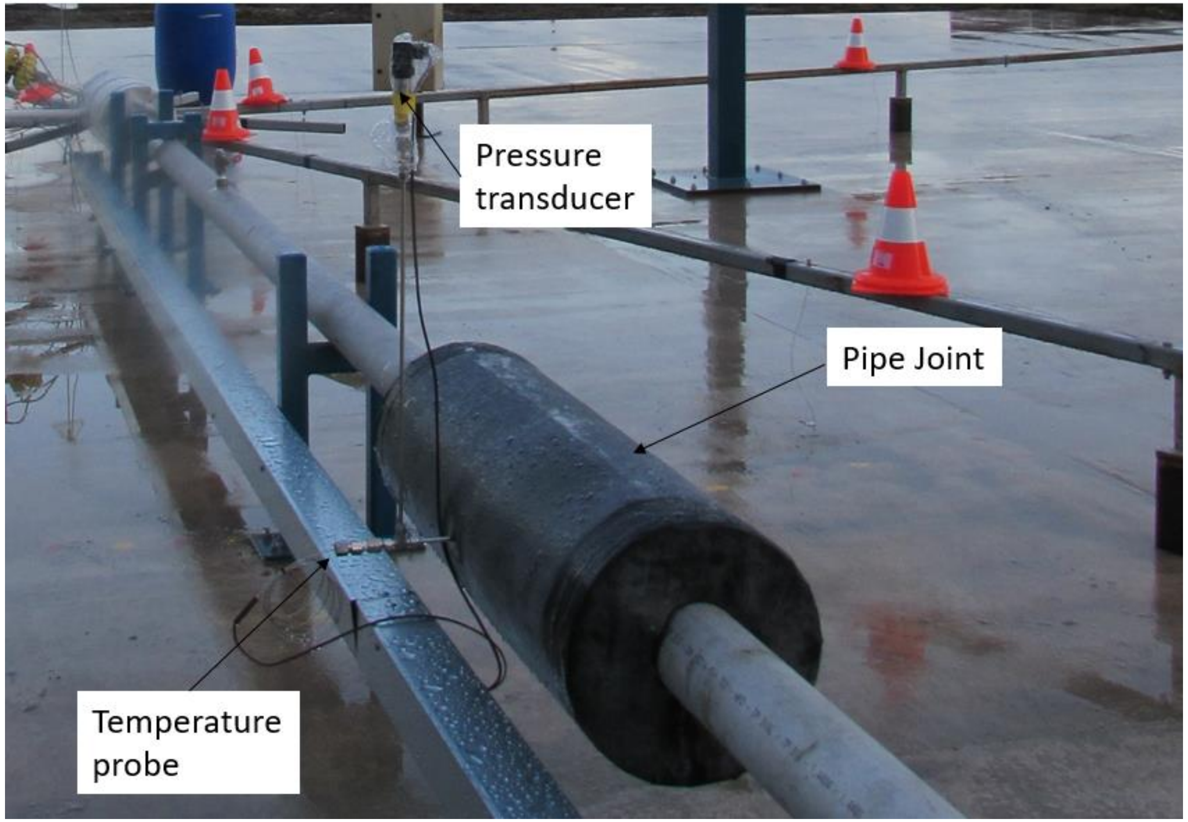
Experimental Arrangements: Bulk LH_2 Delivery

Experimental Arrangements: LH_2 Supply Pipework

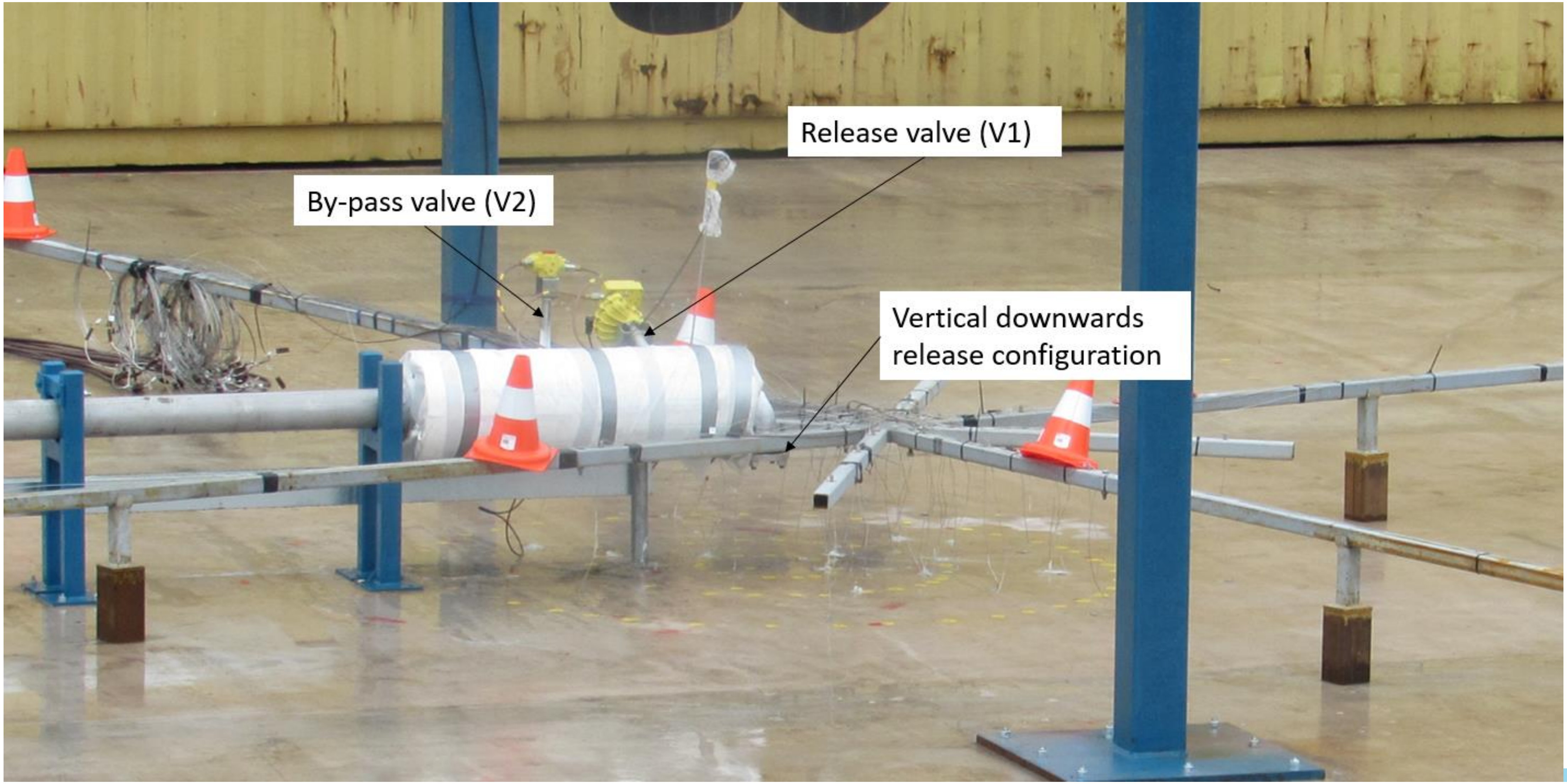
Experimental Arrangements: LH_2 Supply Pipework

- 2” pipe inside 4” pipe
- Vacuum insulated
- Convoluted section for expansion / contraction
- Insulated joints with P, T tapping





Experimental Arrangements: Open Releases

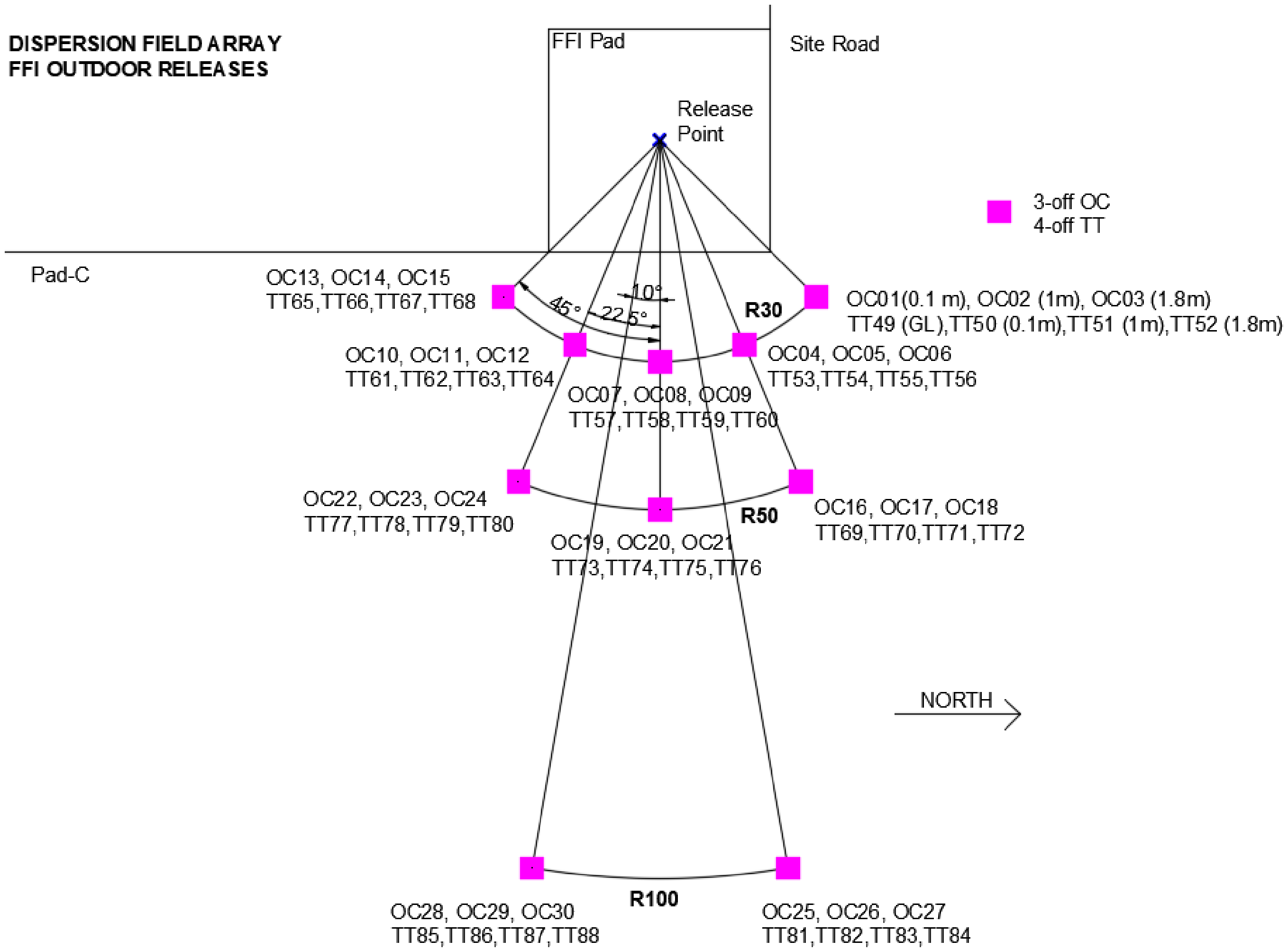


Experimental Arrangements: Open Releases, Near-Field Array

Experimental Arrangements: Open Releases, Field Array

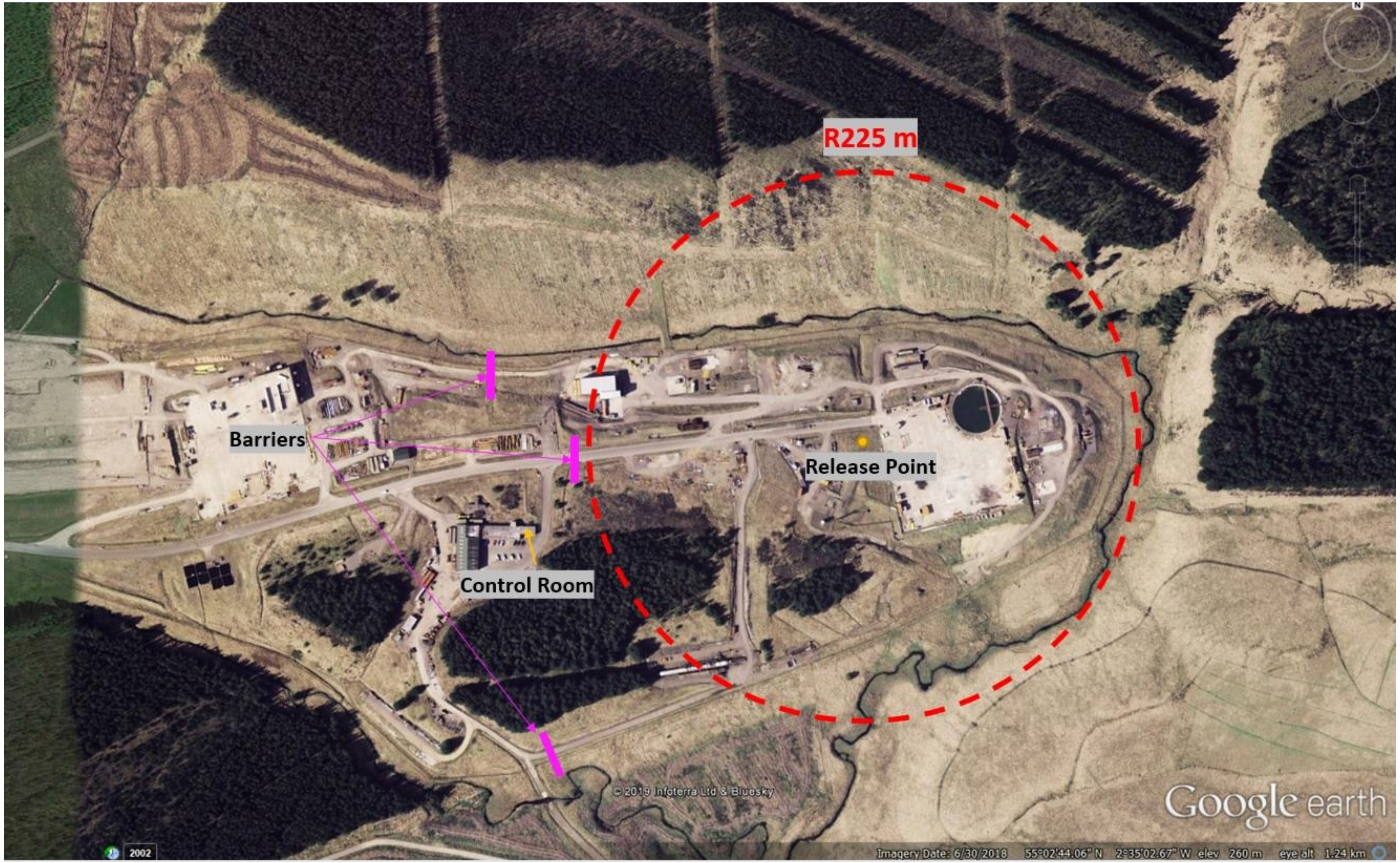
Experimental Arrangements: Open Releases, Field Array

- E.g. Test01



Method

- Purge and cool pipe:
  - N_2 → LN_2 → He_2 → H_2 → LH_2
- Remotely operated from outside Exclusion Zone
- Set Tanker pressure then isolate PBU

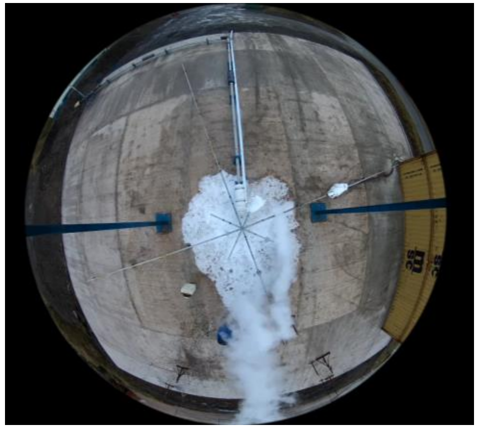
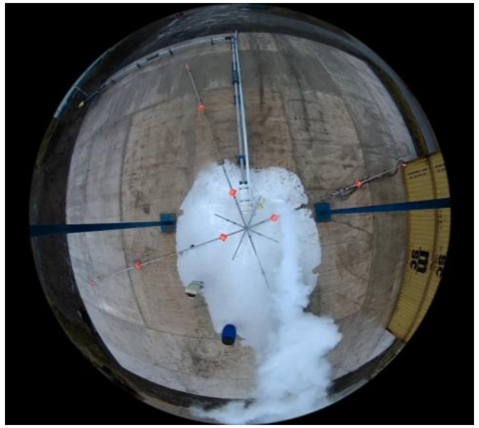
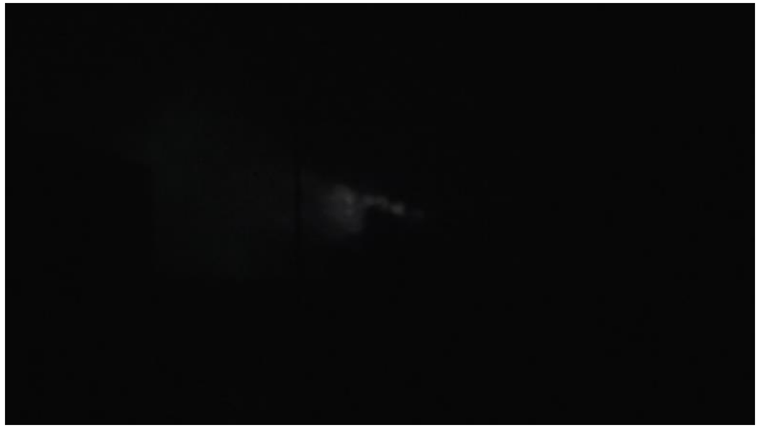


Outdoor Programme

- Variants in:
  - Orientation
  - Ignition Yes/No
  - Initial Tanker Pressure
  - Run Time
  - Wind Speed / Direction

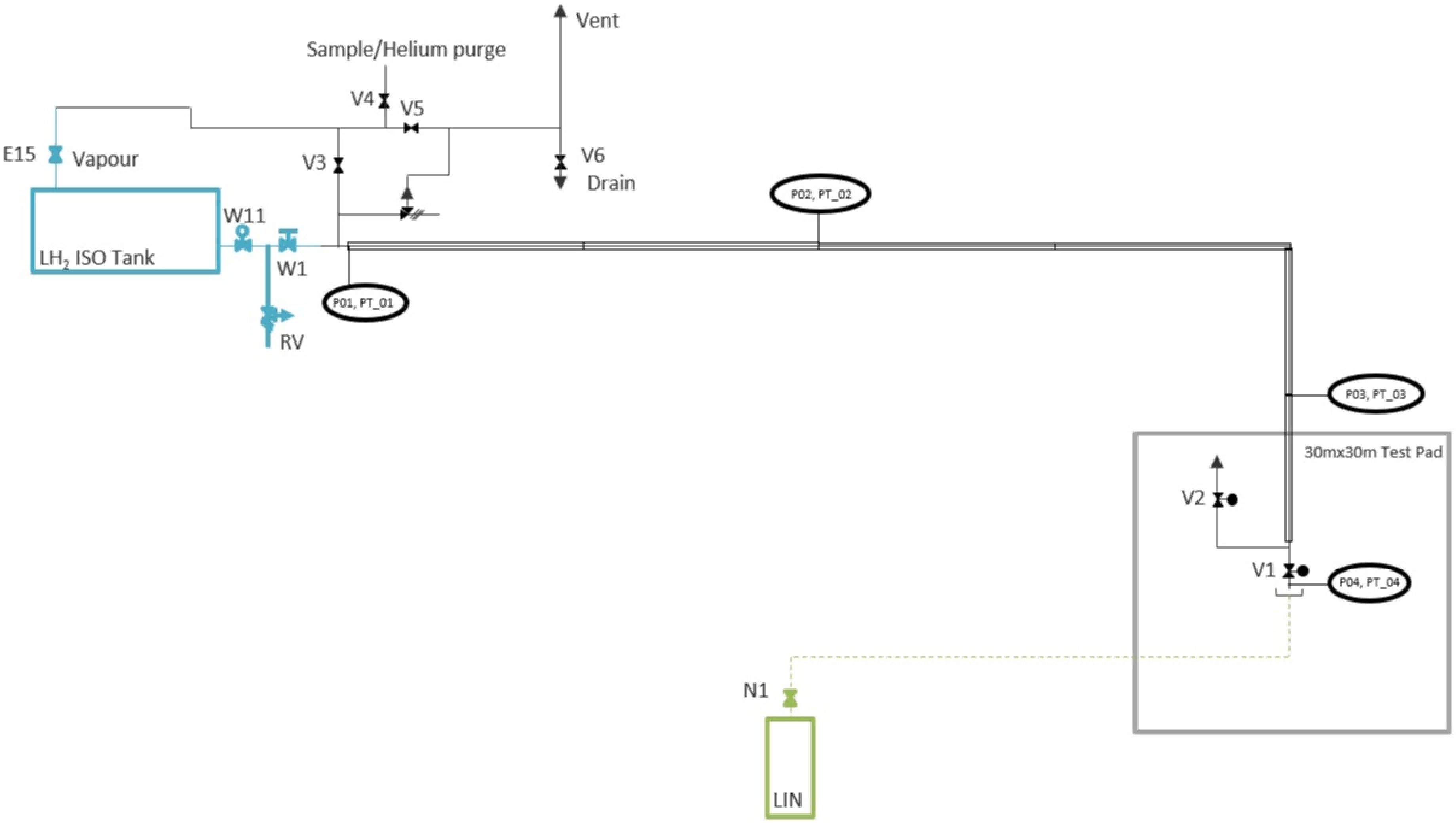
Test No	Release Orientation	Ignition	Initial Tanker Pressure (barg)	Outflow (kg/min)	Run time (min)	Wind Direction	Observations
1	Vertical Downwards	No	2	13.5	13	W-WSW	• First test performed at pressure as received. • All instrumentation in original positions
2	Vertical Downwards	No	6	28.2	8	E-ENE	• Easterly wind present, field array stands re-positioned to the West and to front of ISO container. • Tanker initial pressure increased to achieve higher flow rate (6 barg on tanker prior to release)
3	Vertical Downwards	No	10	43.8	15	W-WSW	• Increase tanker initial pressure to 10 barg to achieve higher flow rates • Back on Westerly wind, instrument stands on West re-positioned to R100 m on East.
4	Horizontal	No	10	49.7	6	W-WSW	• Repeat of Test03 but with a horizontal orientation, co-flowing with wind
5	Vertical Downwards	Yes	10	42.9	6	W-WSW	• Repeat of Test02 but ignited • Suspected voltage interaction between ignitors and release valve. Release had to be re-initiated and left to run again for 2 minutes before ignition at 18m downwind.
6	Horizontal	Yes	10	49.9	3	W-WSW	• Repeat of Test04 but ignited • Ignited on first firework (30 m downwind of release point)
7	Vertical Downwards	No	0.8	9.7	8	W-WSW	• Final release to empty tanker at saturation pressure • Heavy rain present

Videos

	Above	Ground Level	Ignited
Downwards			
Horizontal			

Outflow / Flashing

Schematic experimental set up: overview

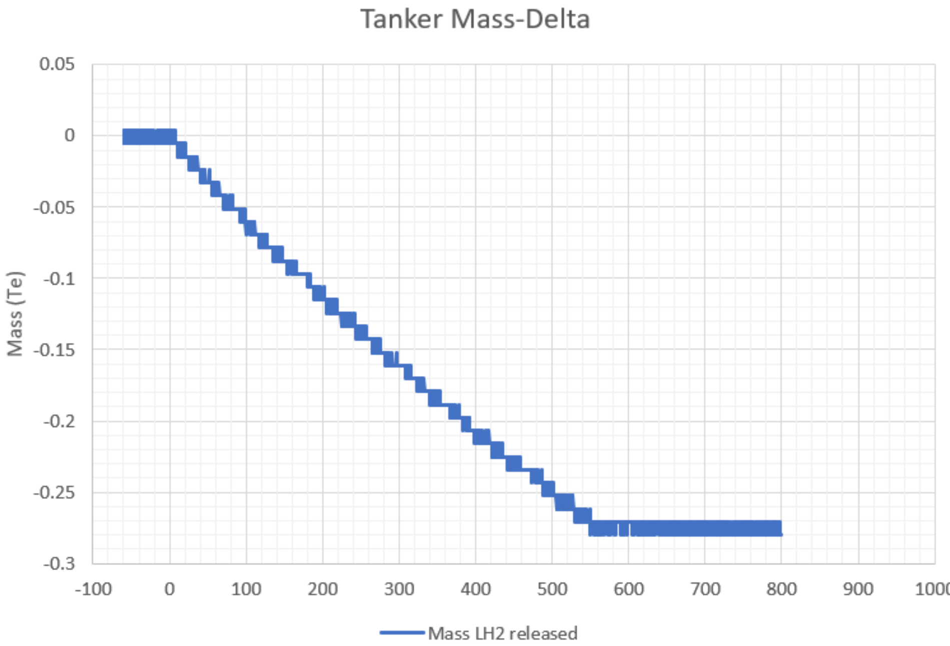


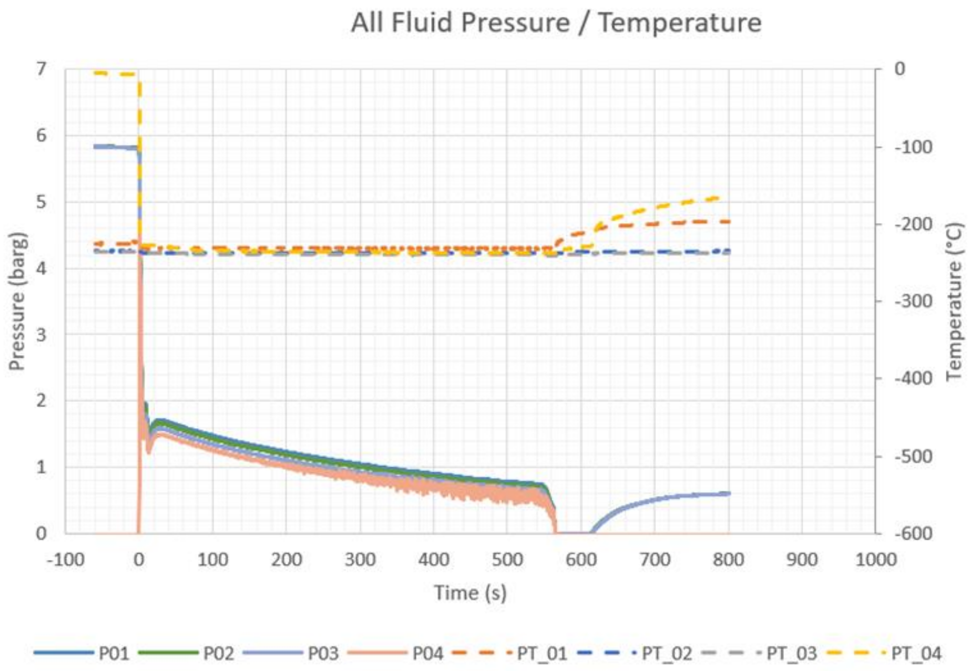
Outflow / Flashing

- Both modelling exercises were able to reproduce the measured mass outflow using only the measured pipeline pressures and knowledge of the geometry and saturation conditions. Using reasonably broad averaging and assumptions on tanker start conditions (i.e. same temp as first test but sub-cooled by PBU)
- Mass outflow rates up to 50 $kg.min^{-1}$ were achieved.
- The liquid / vapour fractions along the pipe during releases were calculated based on the pressure decay and assuming isenthalpic expansion. Releases in all experiments produced high liquid mass fractions (i.e. low mass flashing) with experiments being driven above saturation pressure in the tanker producing higher liquid mass fractions (i.e. little or no flashing in the pipe).

From Experiment: Outflow

- Pick averaging period
- 100-500 seconds here





Sensor	Average	Max	Min	STDEV	units
Mass LH2 released	-	-0.060	-0.253	-	Te
P01	1.07	1.48	0.78	0.20	Barg
P02	1.03	1.43	0.73	0.20	Barg
P03	0.95	1.35	0.61	0.19	Barg
P04	0.87	1.27	0.48	0.19	Barg
PT_01	-231.3	-230.5	-232.3	0.3	°C
PT_02	-237.8	-237.5	-238.1	0.2	°C
PT_03	-239.3	-238.5	-239.9	0.3	°C
PT_04	-236.0	-233.8	-238.1	0.9	°C
MassFlow	0.473				kg/s
Wind_Direction_High	81.9	112.8	41.9	10.4	0.0
Wind_Direction_Low	82.7	118.6	46.1	12.2	Deg
Wind_Speed_High	4.1	6.2	2.4	0.8	m/s
Wind_Speed_Low	3.9	7.7	1.6	1.0	m/s

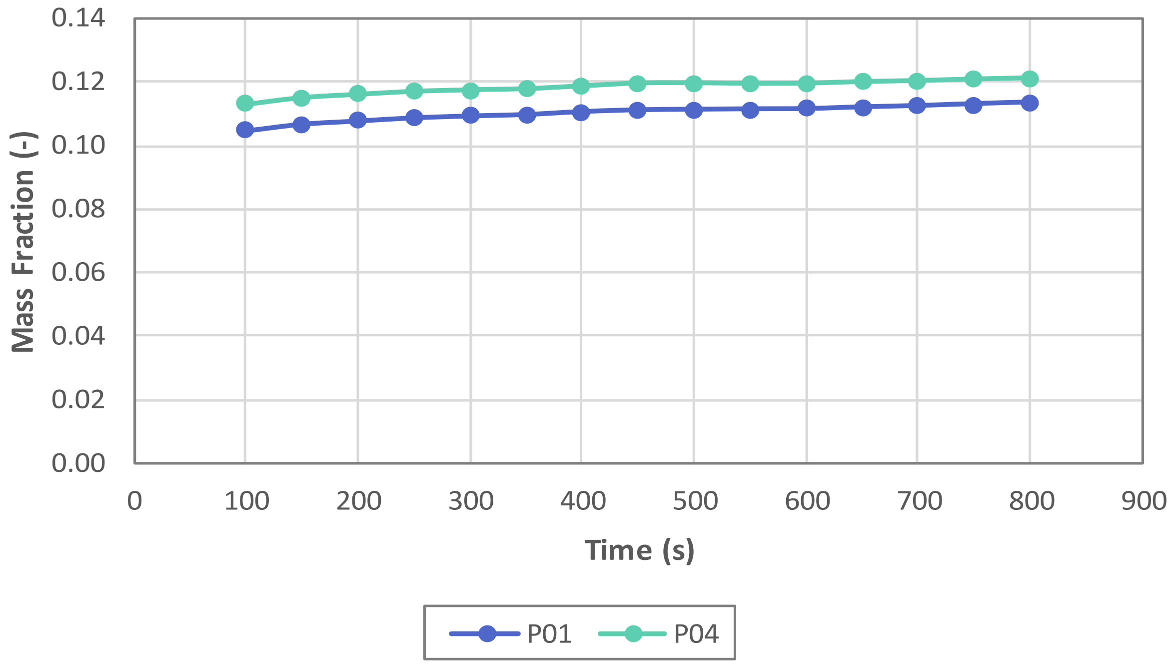
Vapour Quality: FROST

Table 1: Conditions in the pipeline at 100 seconds

Parameter	Location			
	P01	P02	P03	P04
Pressure (barg)	0.342	0.332	0.277	0.241
Temperature (K)	21.32	21.30	21.15	21.05
Vapour quality (mass fraction)	0.107	0.108	0.112	0.115
Vapour fraction (volume fraction)	0.828	0.830	0.842	0.849

Table 2: Conditions in the pipeline at 800 seconds

Parameter	Location			
	P01	P02	P03	P04
Pressure (barg)	0.263	0.245	0.205	0.175
Temperature (K)	21.11	21.06	20.95	20.86
Vapour quality (mass fraction)	0.113	0.115	0.118	0.121
Vapour fraction (volume fraction)	0.845	0.848	0.857	0.862



- Assuming saturation conditions in the pipe
- Test without PBU gives 11-12% of the mass as vapour at the end of the supply pipe

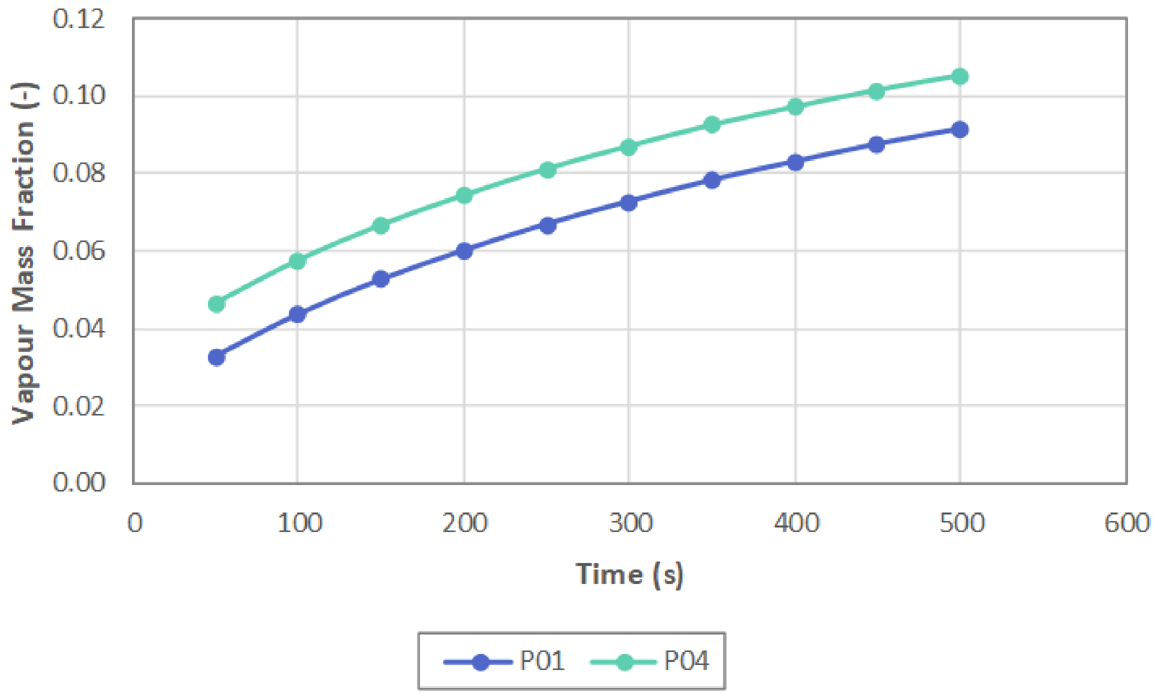
Vapour Quality: FROST

Table 1: Conditions in the pipeline at 50 seconds

Parameter	Location			
	P01	P02	P03	P04
Pressure (barg)	1.651	1.605	1.527	1.442
Temperature (K)	24.00	23.92	23.79	23.64
Vapour quality (mass fraction)	0.033	0.036	0.041	0.047
Vapour fraction (volume fraction)	0.406	0.432	0.475	0.517

Table 2: Conditions in the pipeline at 500 seconds

Parameter	Location			
	P01	P02	P03	P04
Pressure (barg)	0.791	0.751	0.674	0.605
Temperature (K)	22.39	22.30	22.13	21.97
Vapour quality (mass fraction)	0.091	0.094	0.100	0.105
Vapour fraction (volume fraction)	0.752	0.763	0.782	0.798



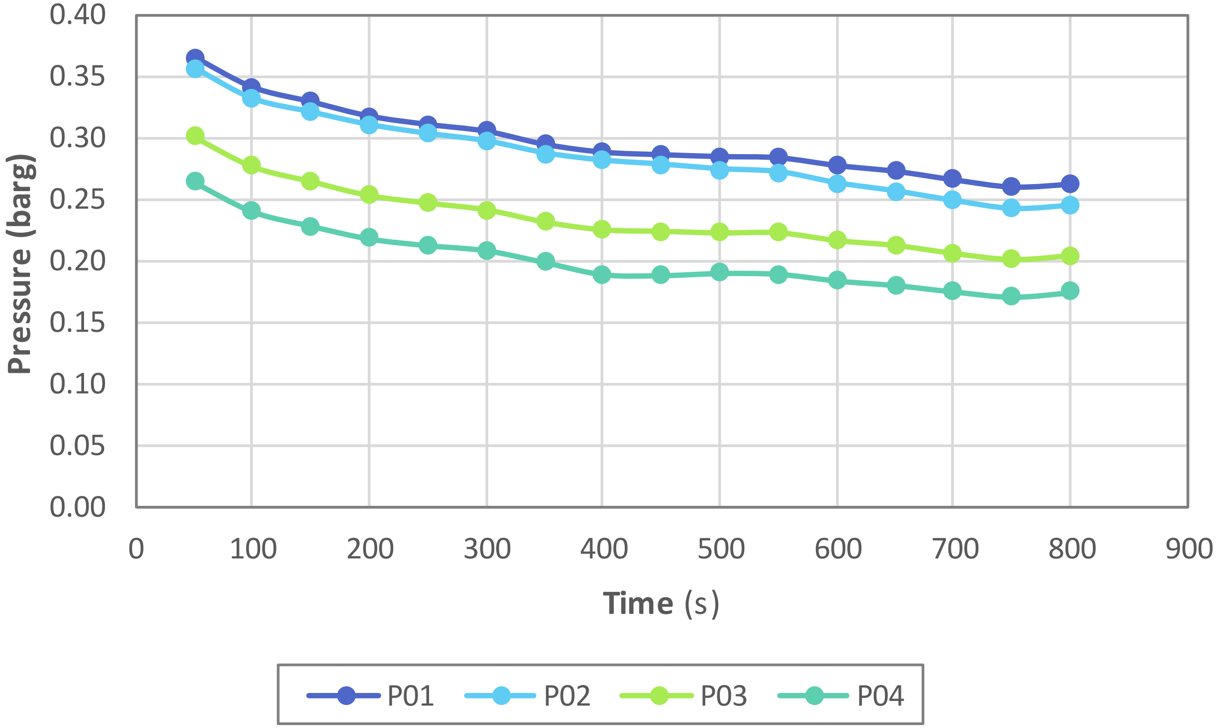
- With PBU – vapour fraction smaller

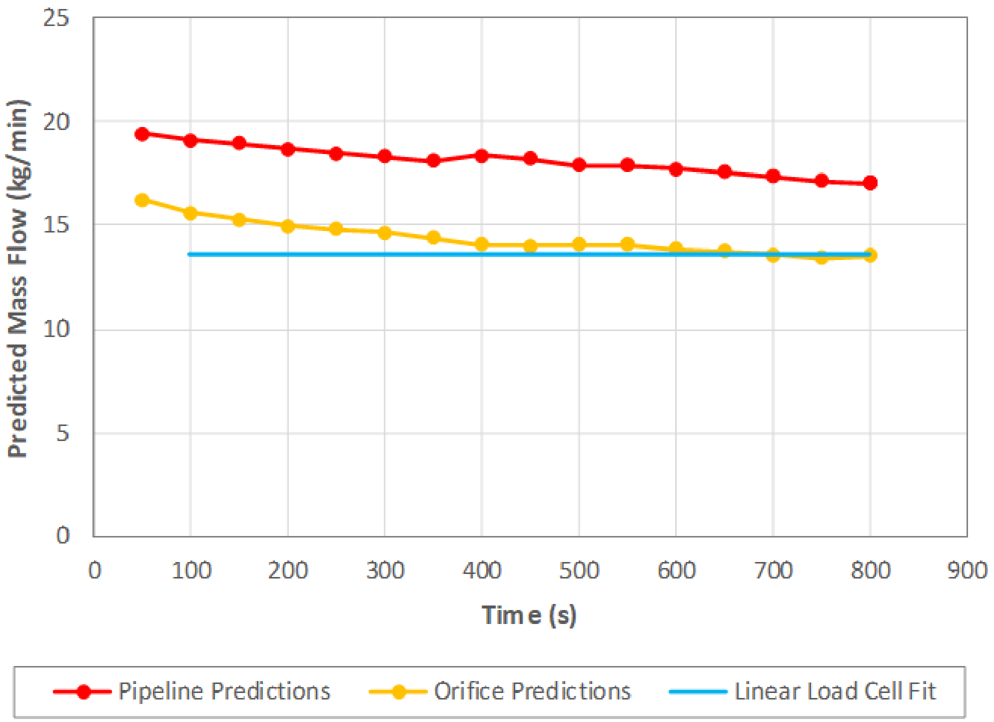
Outflow: FROST

- Using pressure drop along pipeline

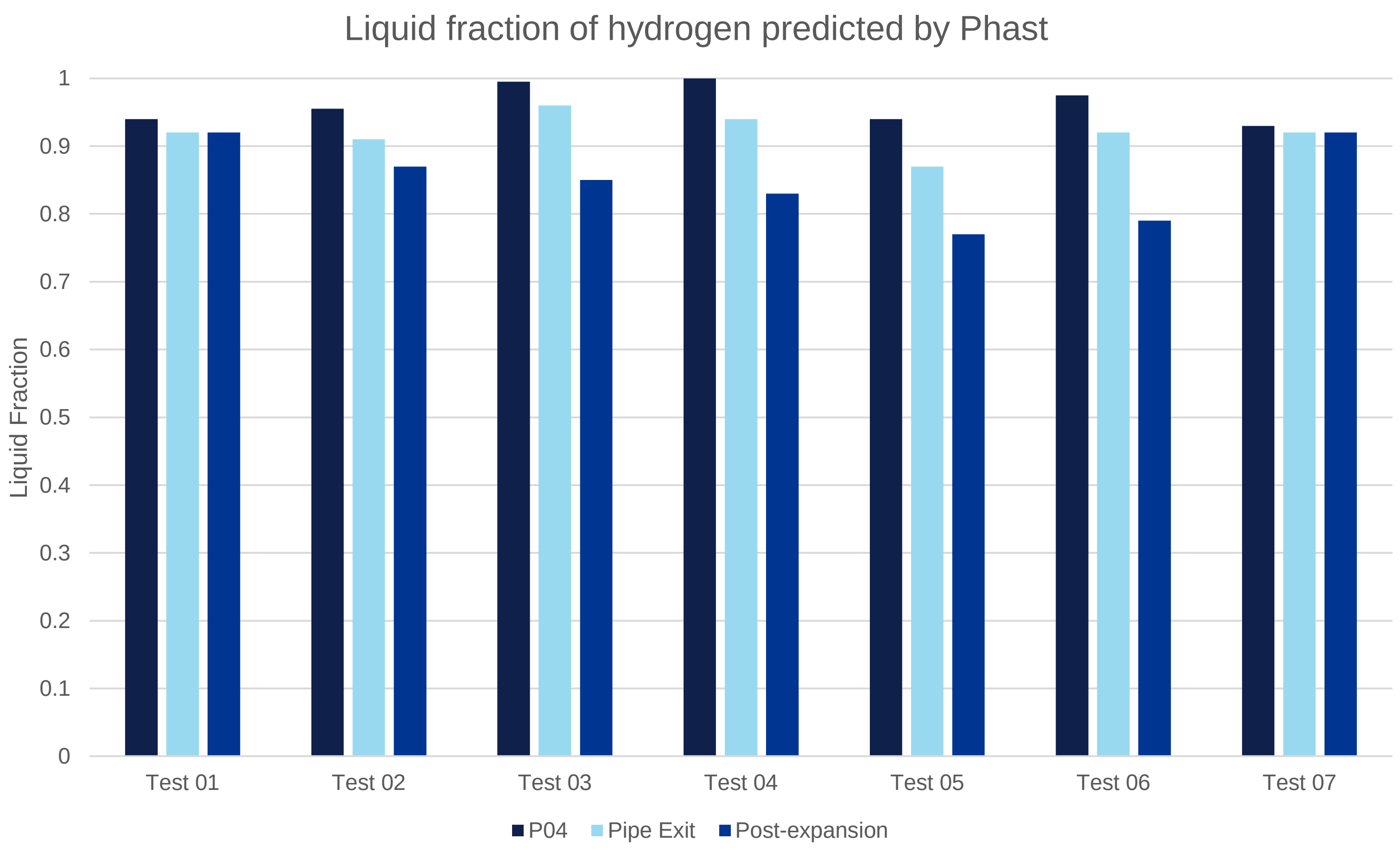
OR

- Orifice calculation



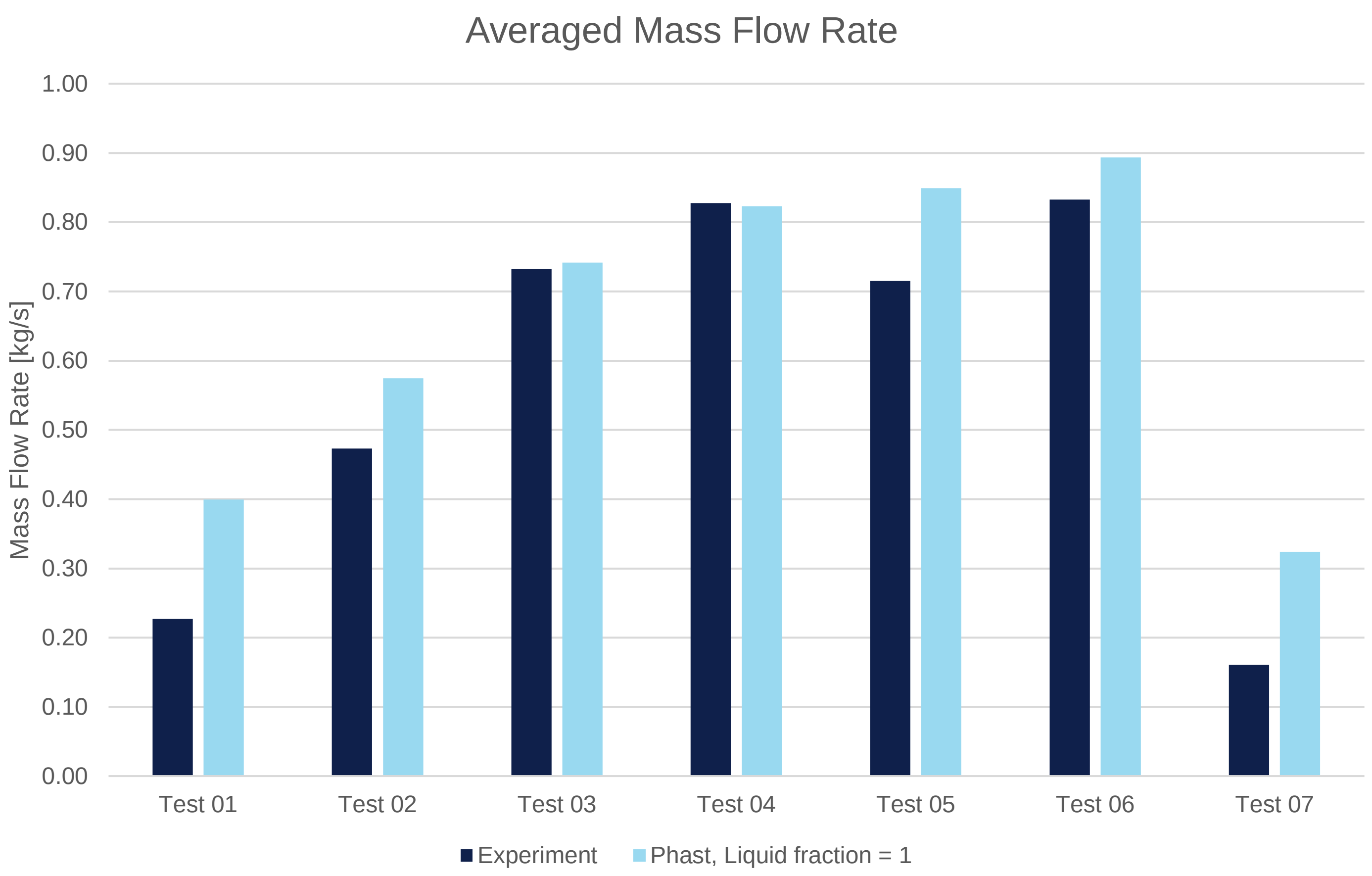


Phast liquid fraction predictions (averaged)



- Standard Phast leak model
- Match Phast and experimental release rates
- Use Phast to deduce liquid fraction
- Indicates 90% or more liquid mass fraction at P04 for all cases

Flow rates: experiments vs Phast predictions

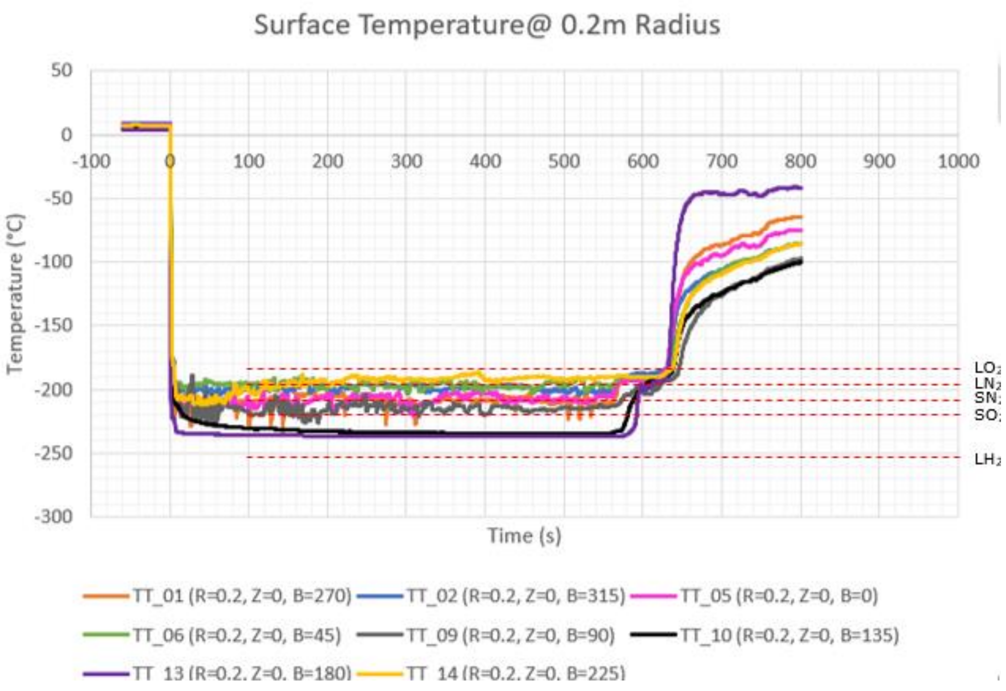


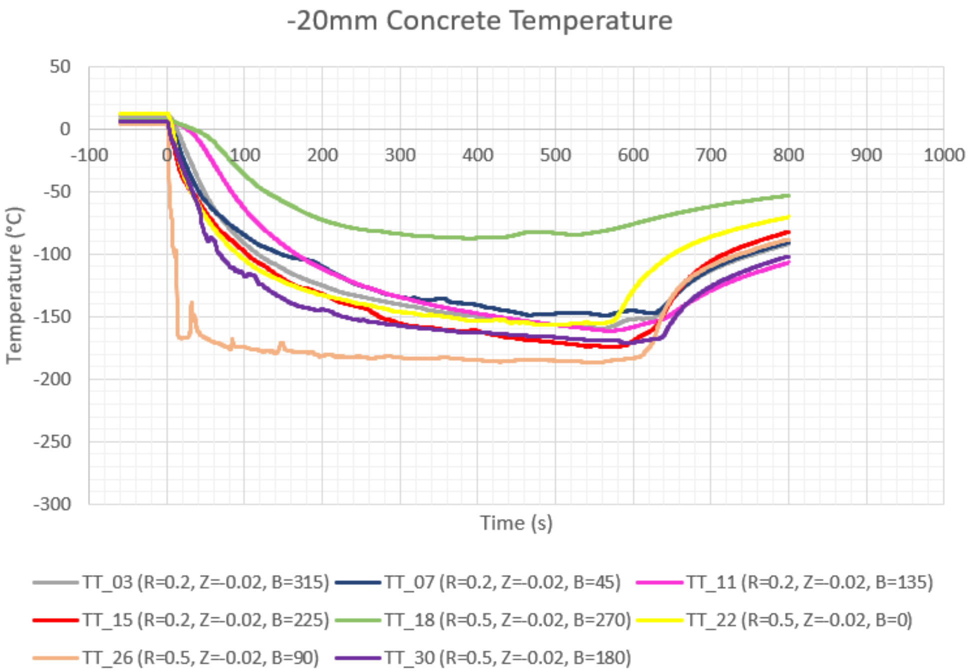
- Standard Phast leak model
- Averaged pressure at P04
- Saturation temperature
- Assume liquid fraction 1.0
- Flow rate predictions: Generally good agreement

Pooling / Rainout

From experiment Pooling / Rainout

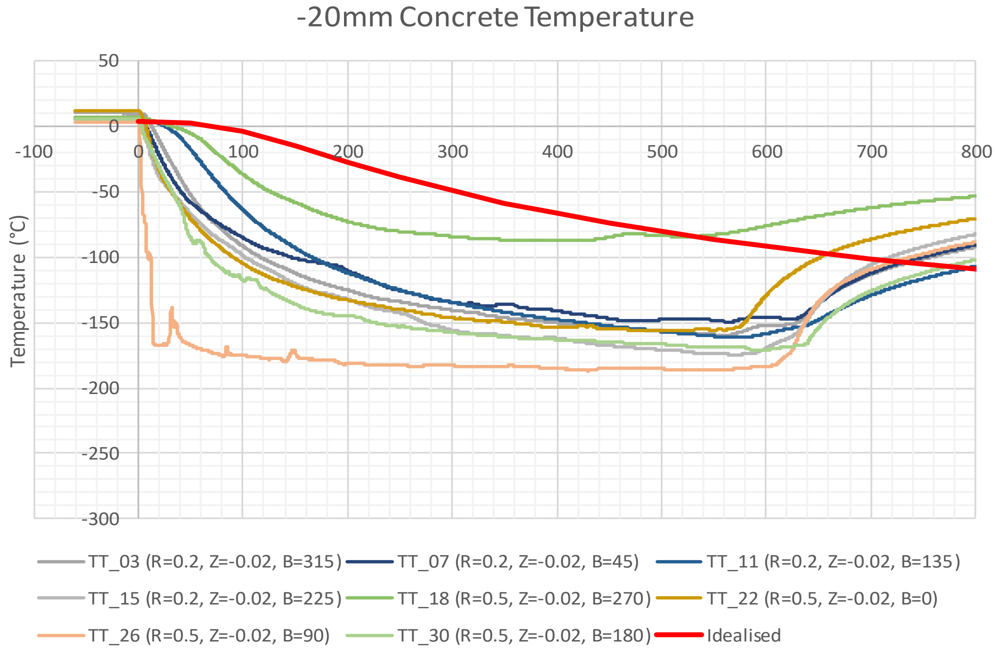
- Surface temperature measurements show evidence of LH_2
  - Difficult to distinguish between 2-phase and actual pool
  - Release in this example (Test02) stops circa 560 seconds
    - Enduring L-Air components ~80 seconds after release
  - No LH_2 evidence beyond 0.5m from release
- No evidence of rainout in horizontal releases

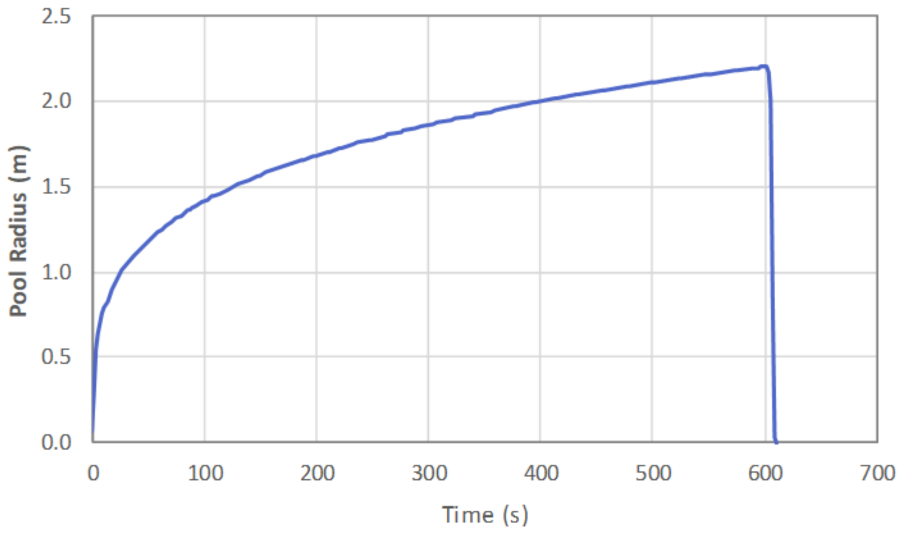


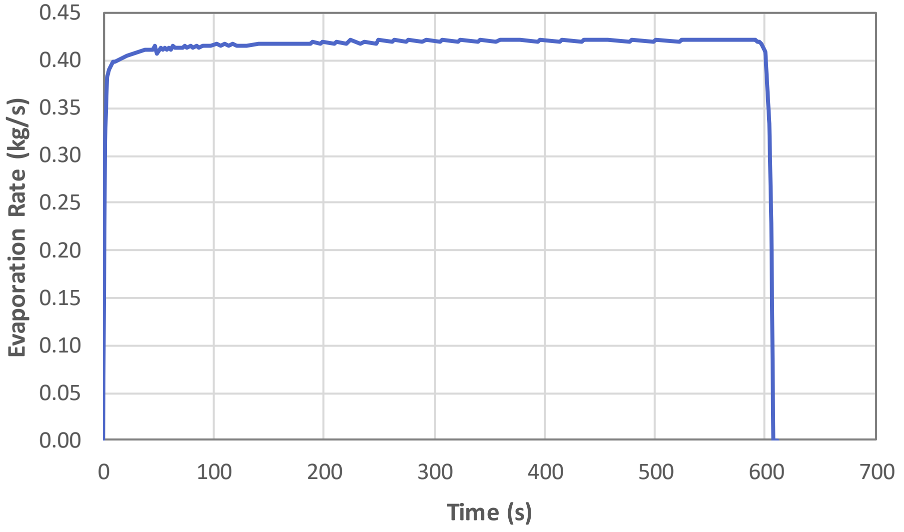


From FROST Pooling / Rainout

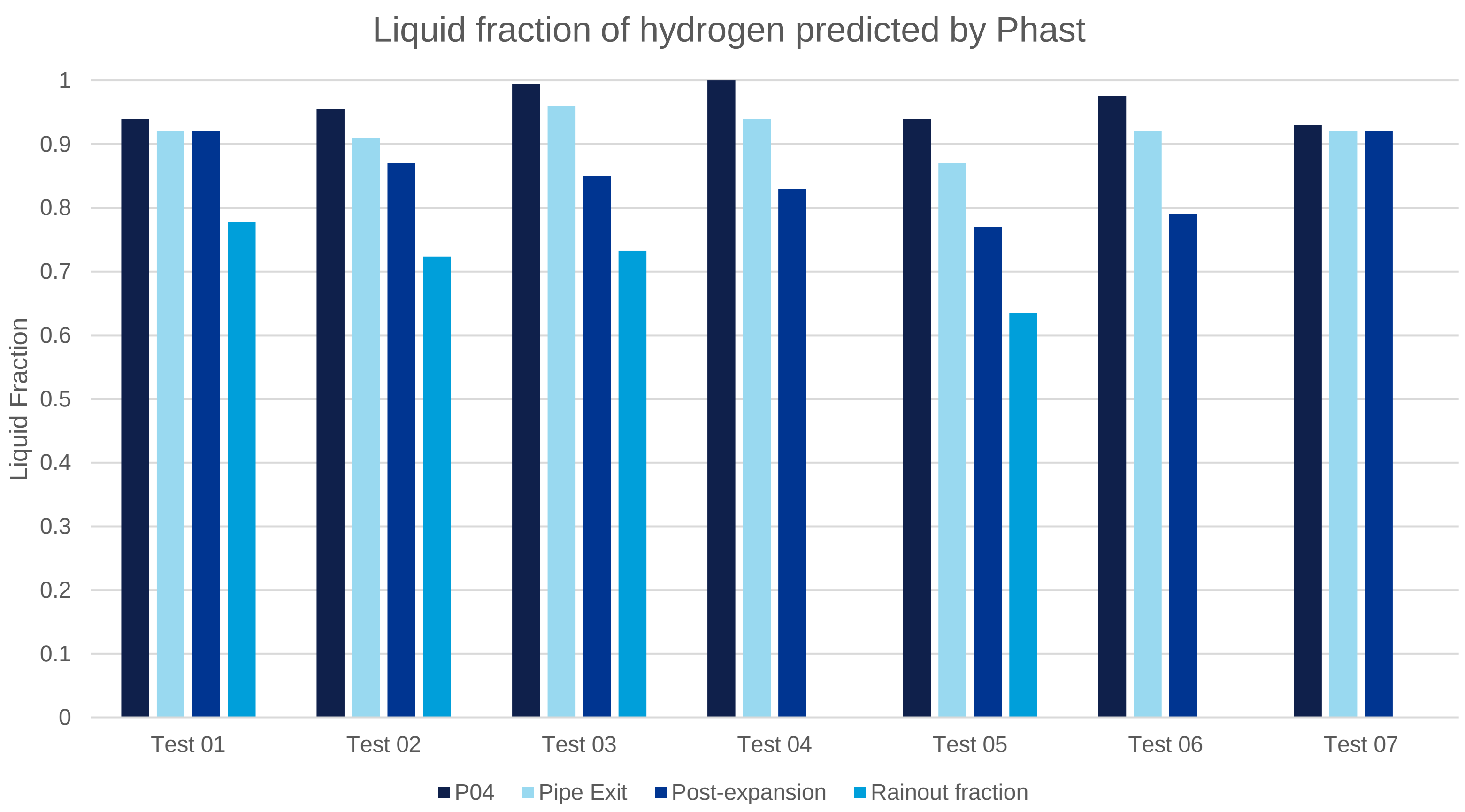
- Higher predicted LH_2 pool radius than observed
- Assume 85% by mass hitting ground
- Concrete responding slower in model than experiment







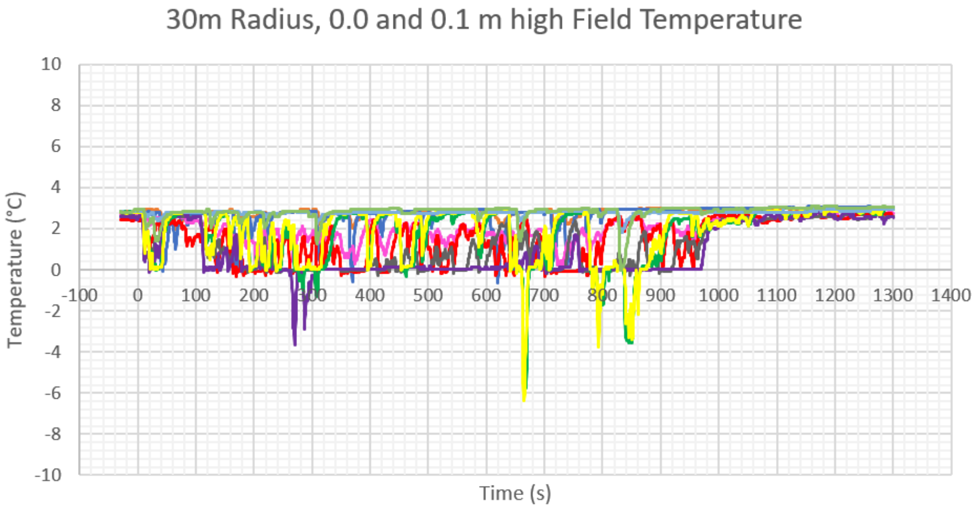
PHAST
How much LH2 rains out?

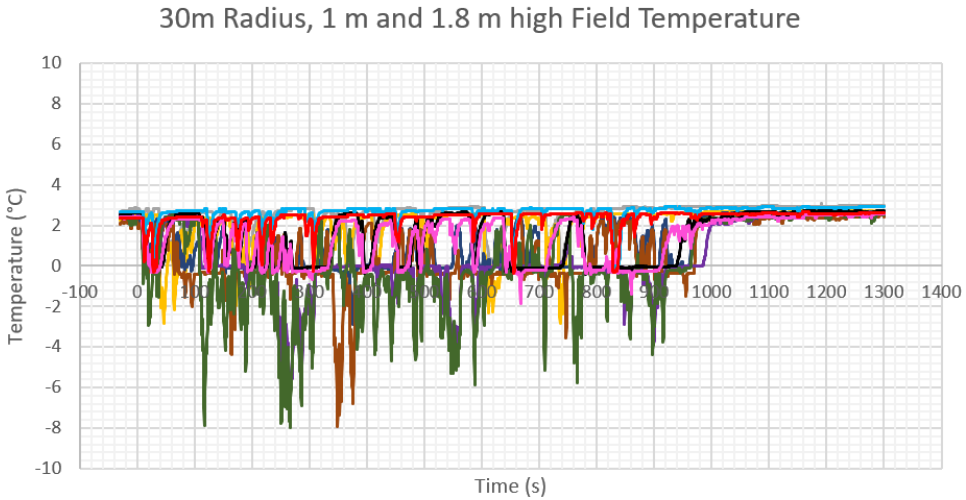


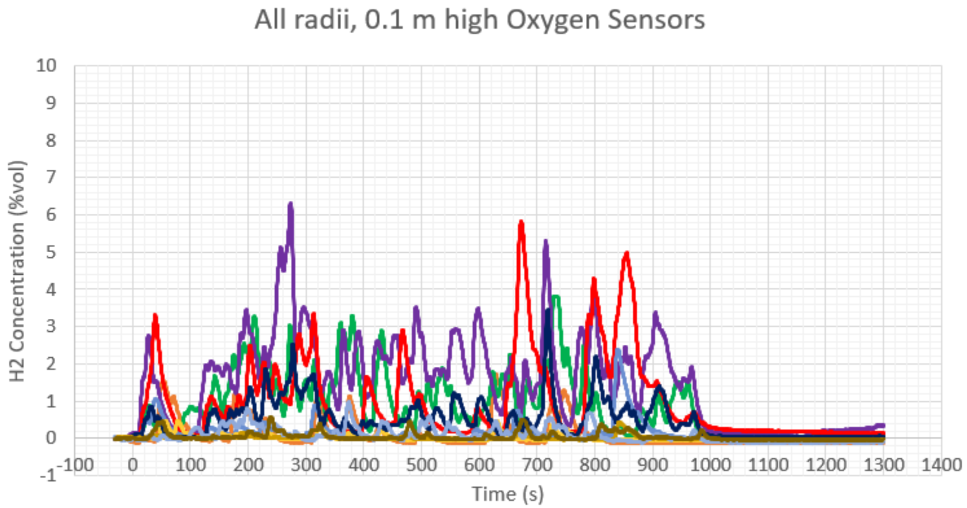
- Physical process:
  - Flashing
  - Air entrained
- Vertical releases T01 to T05 all predicts more than 60% of the liquid to hit the test pad (rainout)
- Horizontal release T04 and T06: no rainout

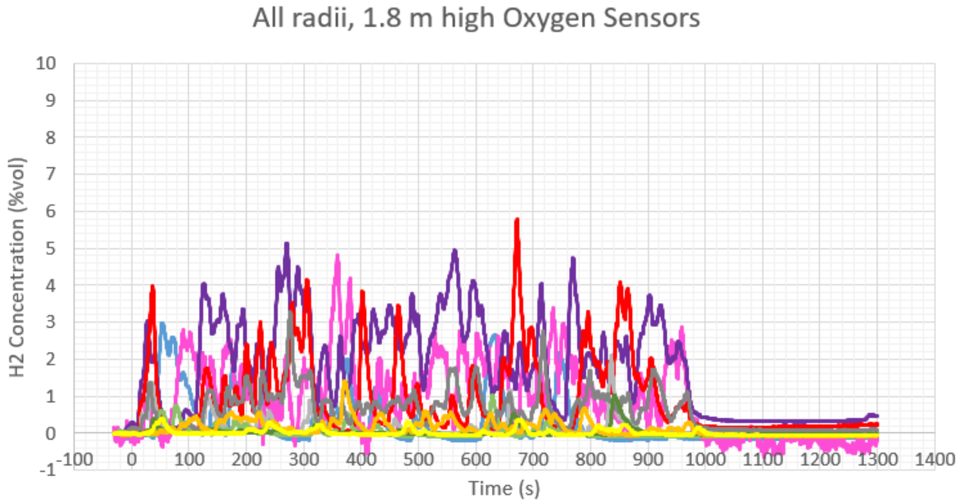
Dispersion / LFL limits

From experiment: Dispersion, LFL Limits

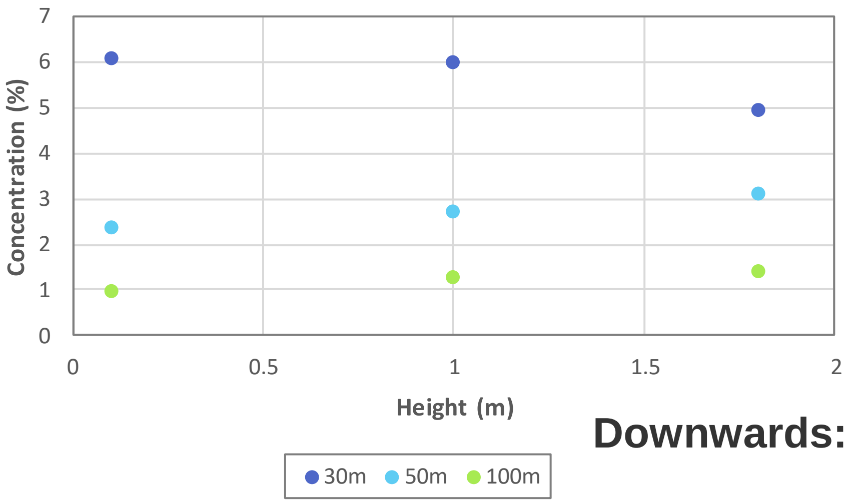


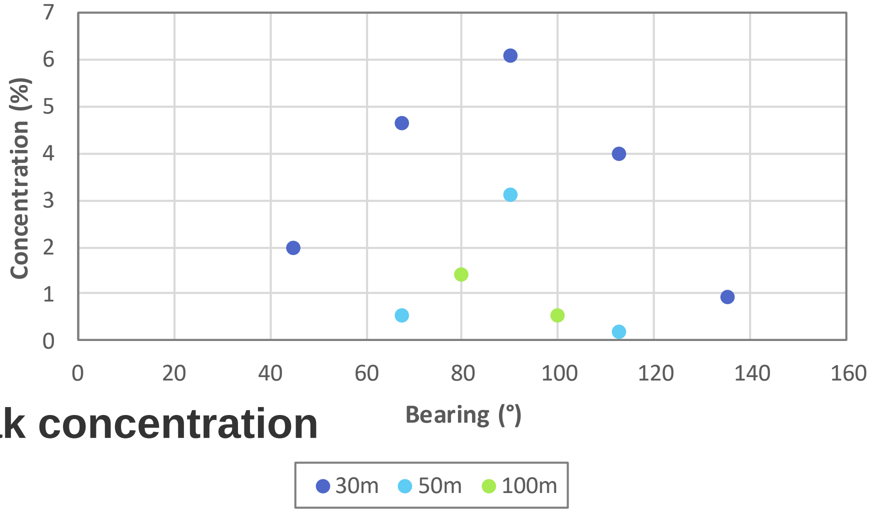




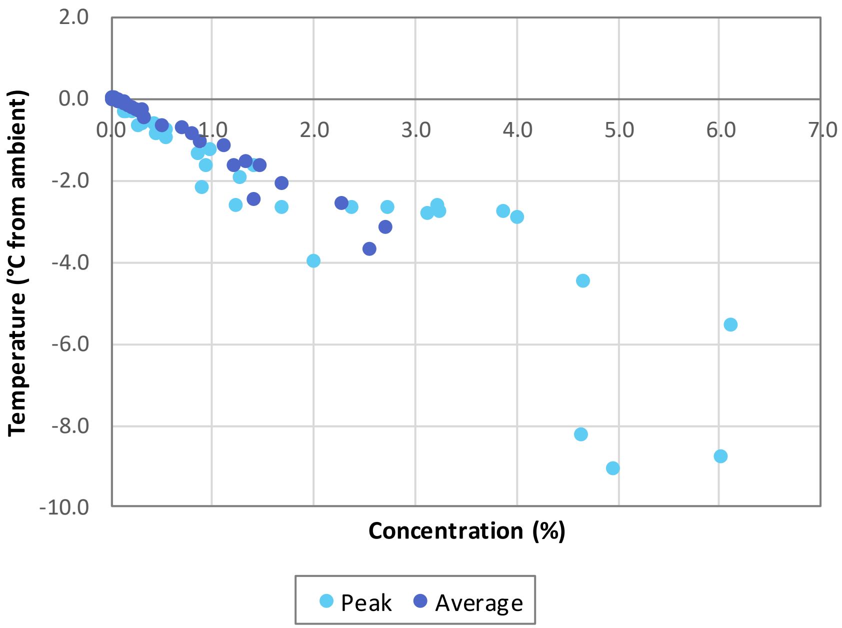


From experiment: Dispersion, LFL Limits



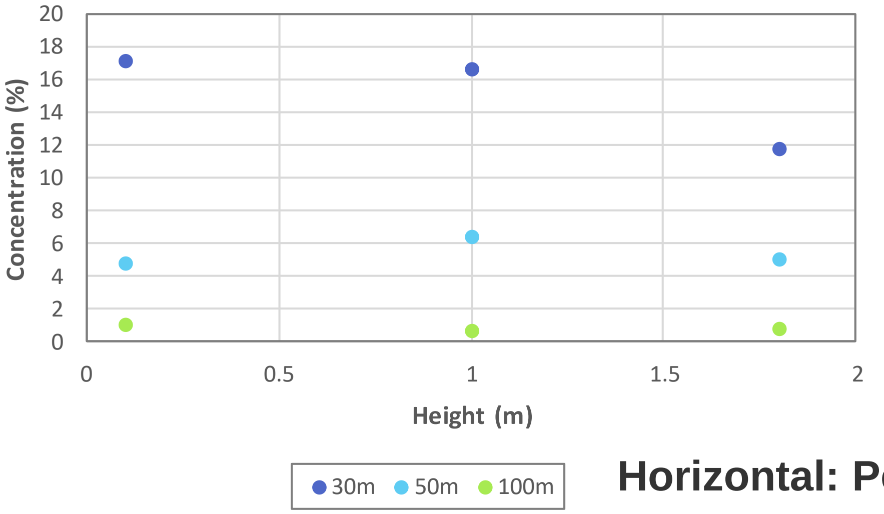


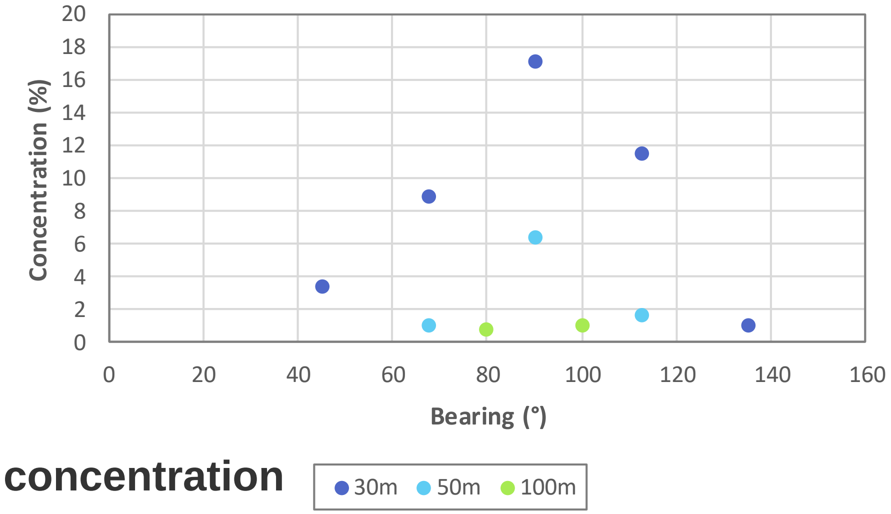
Downwards: Peak concentration



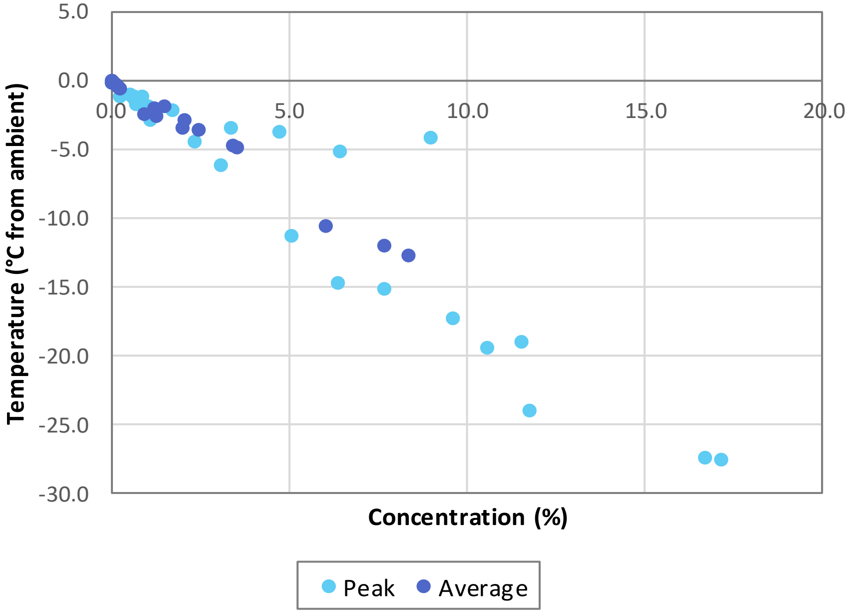
- Generally:
  - Increased concentration → decreased temperature
  - Higher concs at higher positions 50 and 100m
  - Not so at 30m
  - LFL not exceeded in downward past 30m

From experiment: Dispersion, LFL Limits



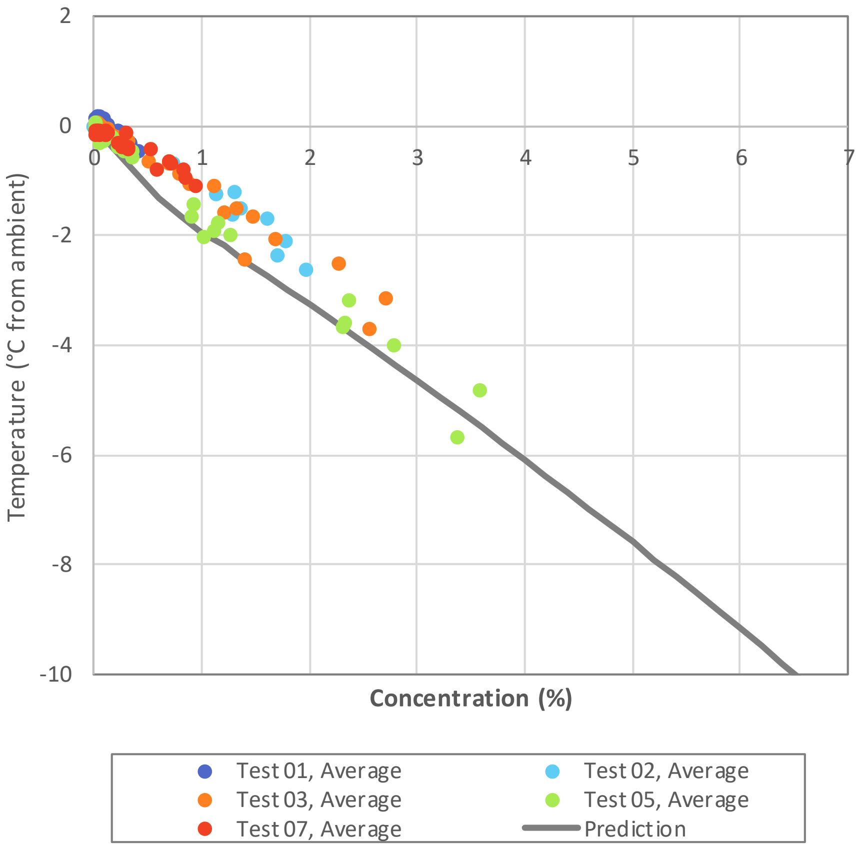


Horizontal: Peak concentration



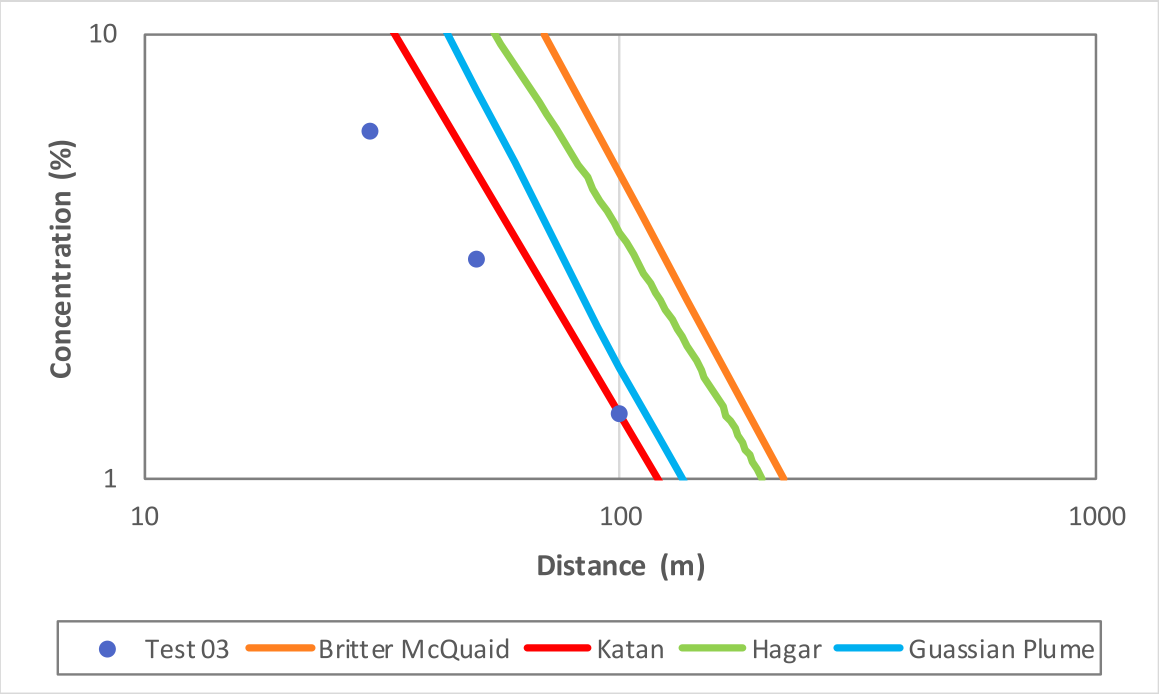
- Generally:
  - Increased concentration → decreased temperature
  - Lower concs at higher positions 30 and 50m
  - Not so at 100m?
  - LFL not exceeded in horizontal past 50m

From GasVLE: Dispersion, LFL Limits



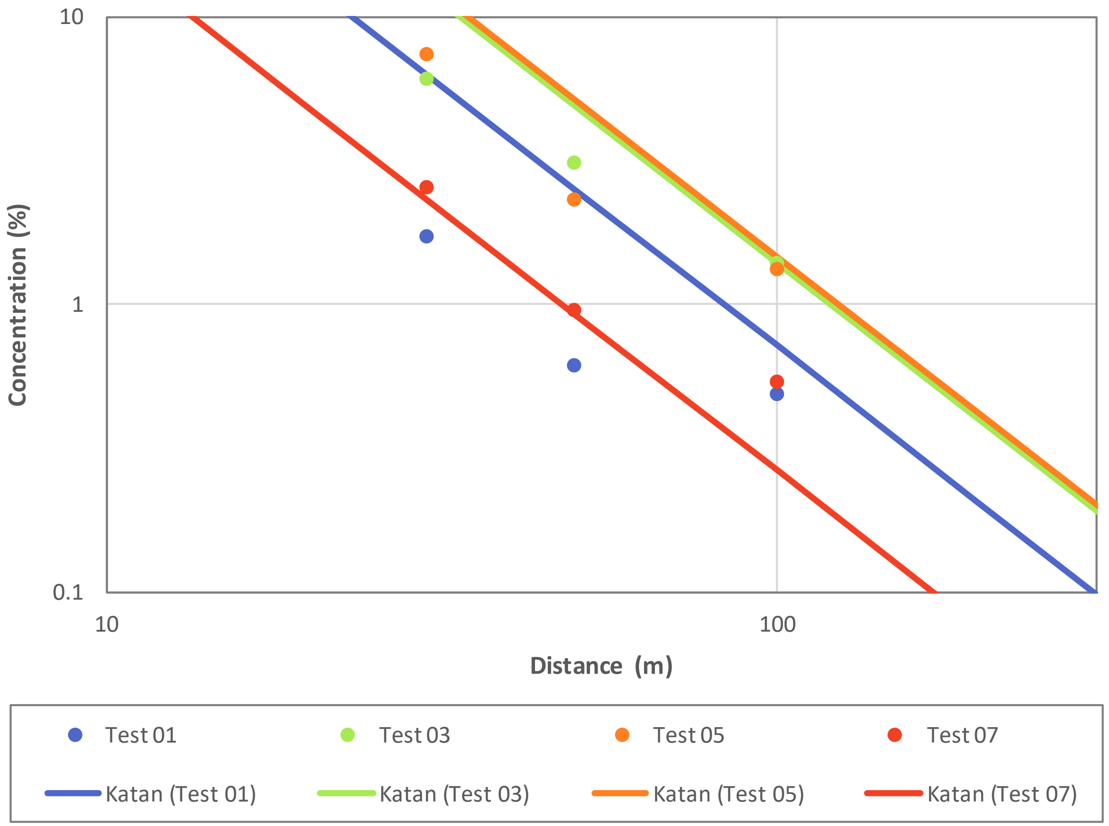
- GasVLE prediction
  - Does not allow for heat transfer from the ground

From FROST:



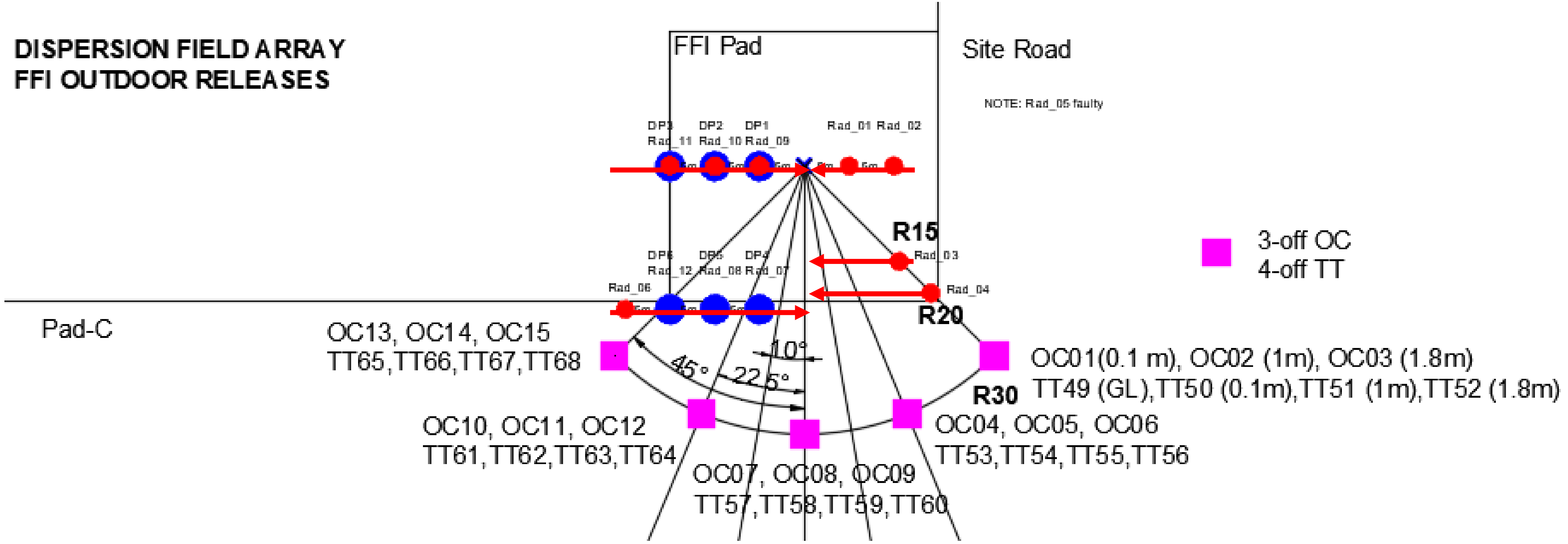
- Test03 vs various models / correlations

- Various tests versus Katan corellation



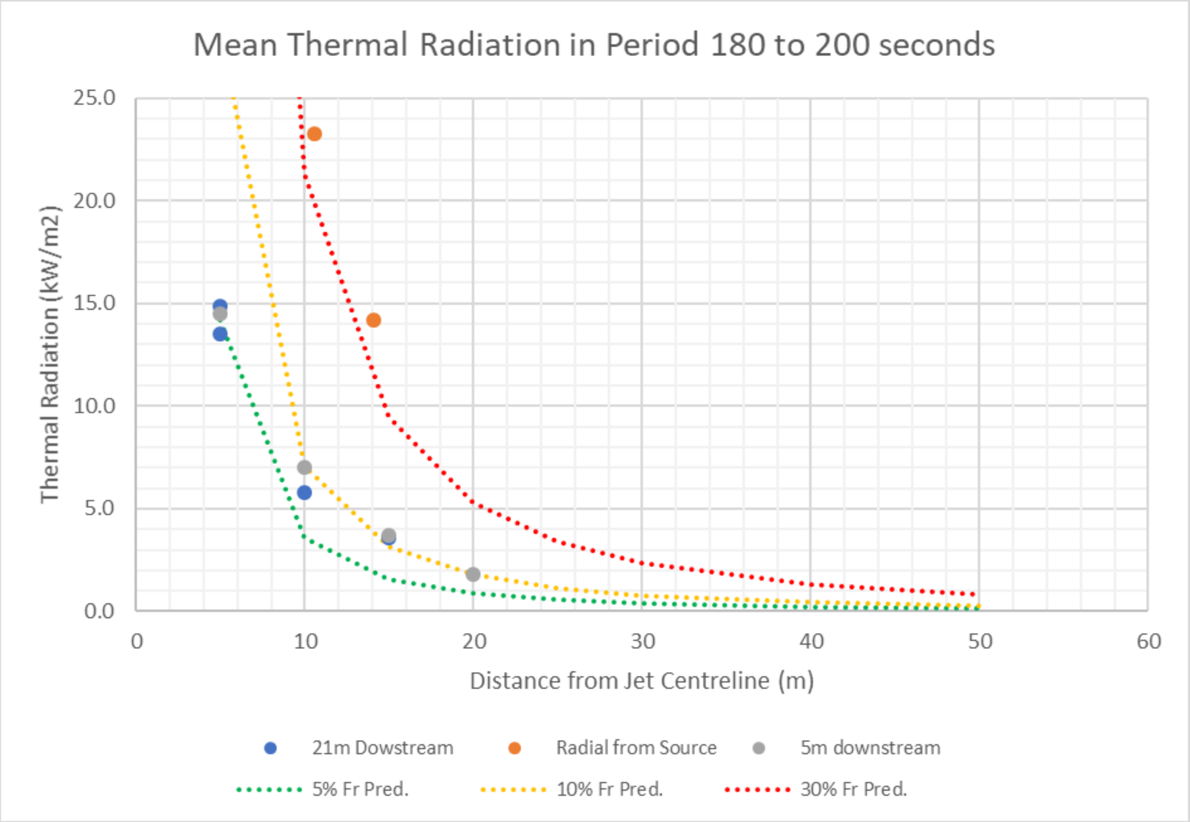
Thermal Radiation

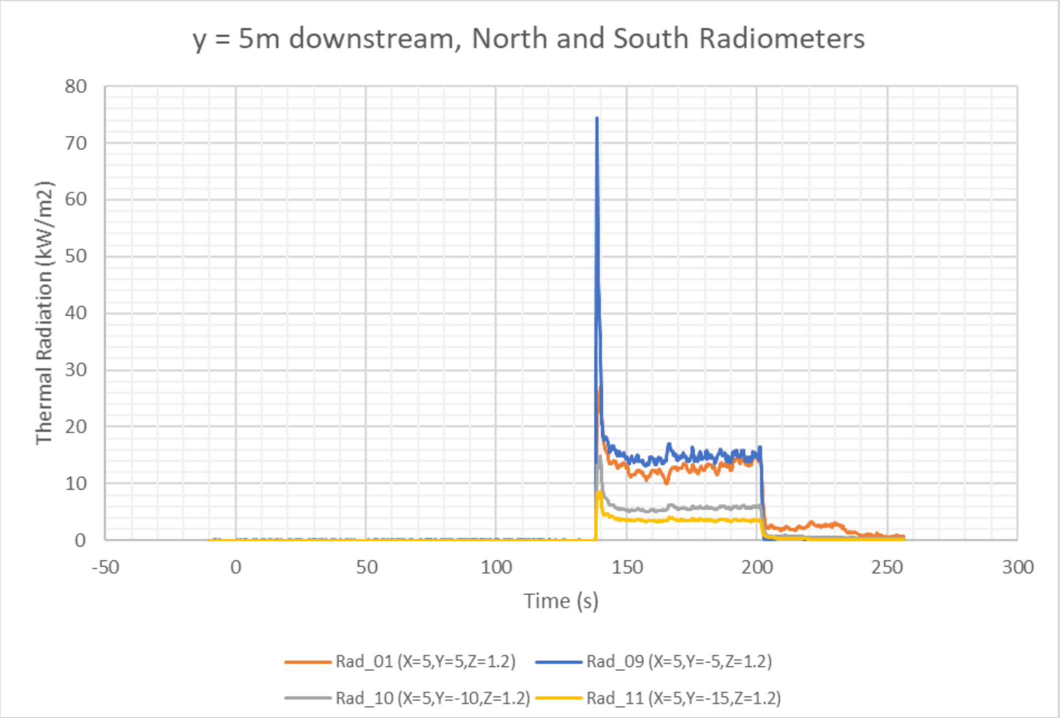
Thermal Radiation

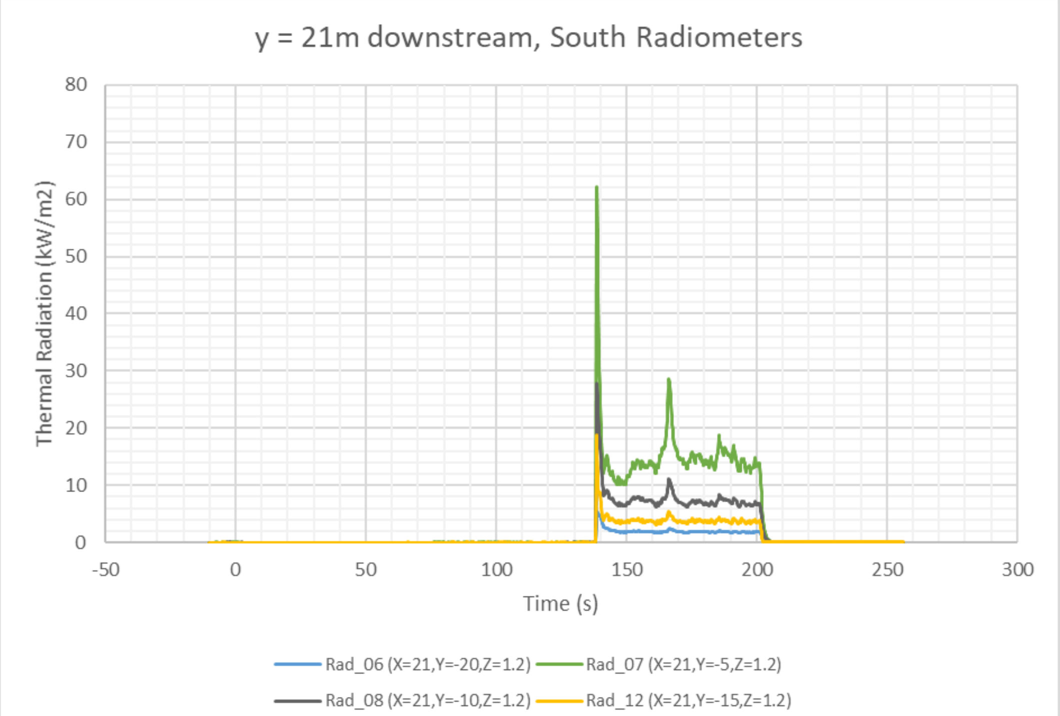


Thermal Radiation

- Seems to fall with r^{-2}
- Initial fireball ~4-5 times higher flux than steady state
- Curious that radial sensors higher than normal sensors



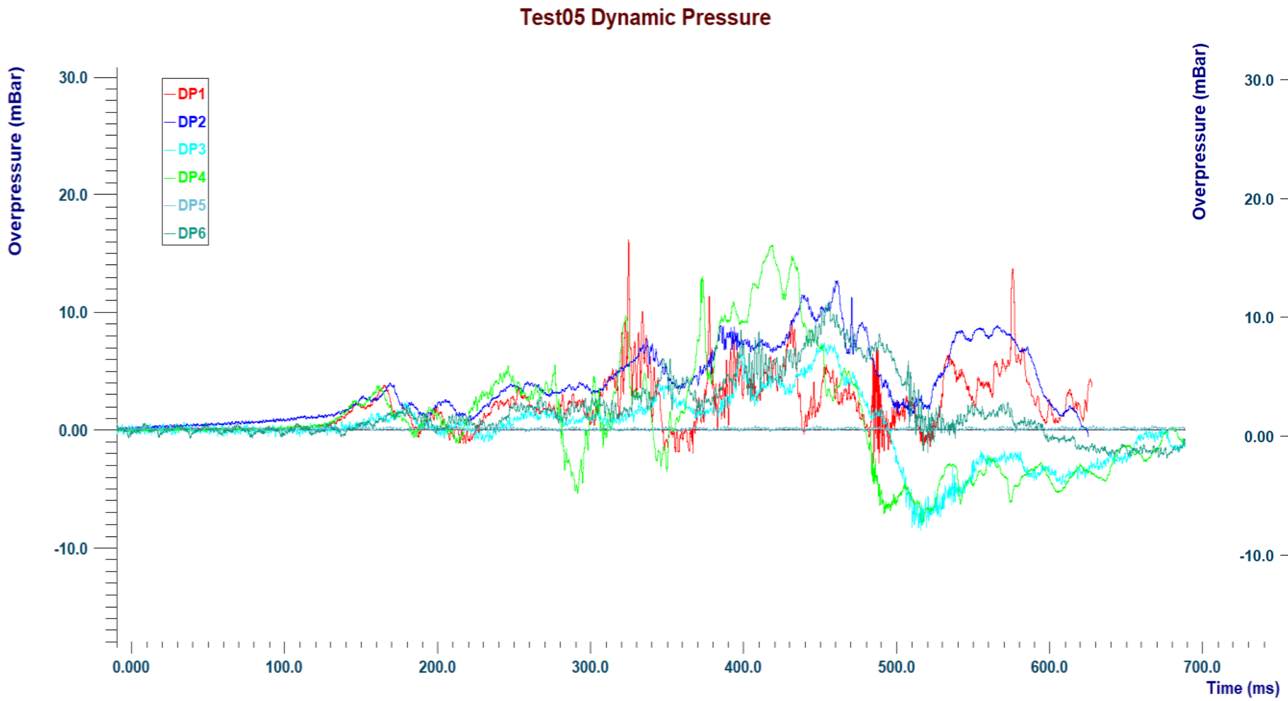




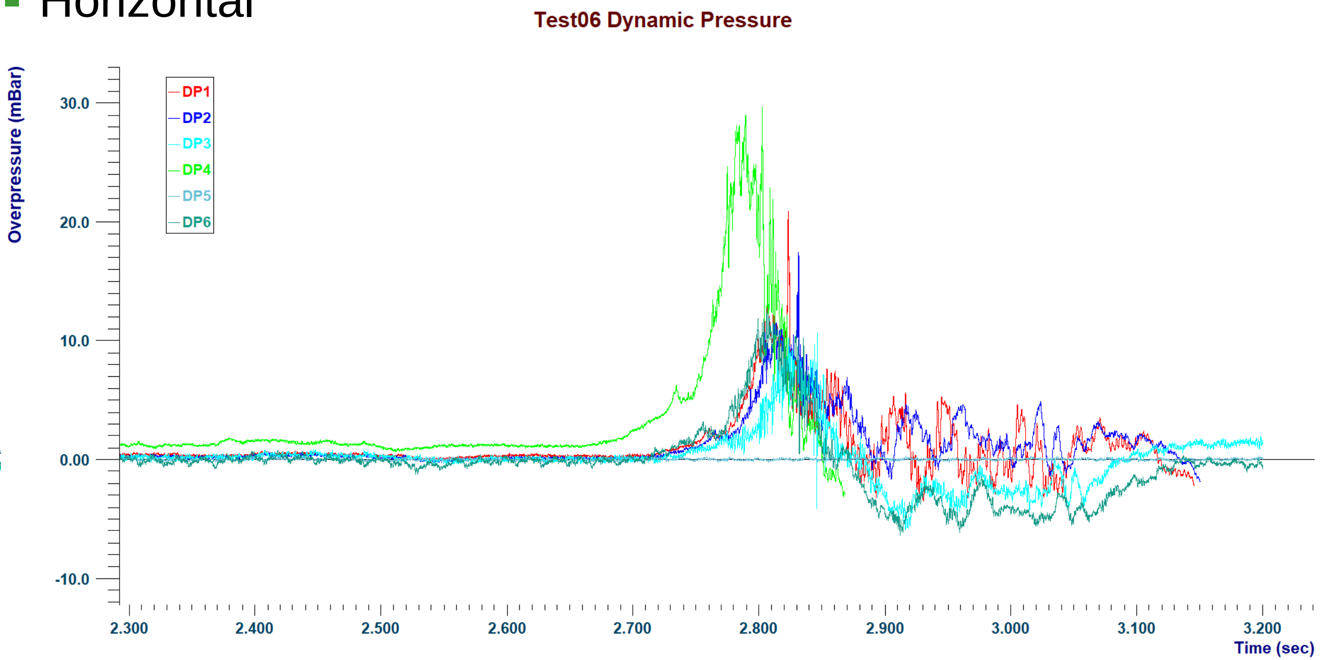
Explosion Effects

Explosion Effects

- Downwards



- Horizontal



Questions?

Thanks for your attention

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