

PRE-SLHY

WP5 – Combustion

LH2 Safety Workshop

March 6, 2019, Bergen, Norway

Pre-normative REsearch for Safe use of Liquid HYdrogen

223
1966



Work package 5: Combustion



Work package number	5		Start Date or Starting Event			Month 10	
Work package title	Combustion						
Participant number	1	2	3	4	5	6	7
Short name of participant	KIT	AL	HSL	HySafe	NCSR	Pro-Science	UU
Person/months per participant:	6	4	4		4	12	4

E5.1 Cryogenic hydrogen jet fire experiments with detailed temperature and heat flux measurements (PS, KIT)

E5.2 Flame propagation regimes at cryogenic temperatures (PS, KIT)

E5.3 Flame propagation over a spill of LH2 (PS, KIT)

E5.4 BLEVE (KIT)

E5.5 LH2 Combustion with congestion/confinement variation (HSL)

		2018												2019												2020											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O		
	Preslhy	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34		
	WP 5																																				
	E5.1																																				
	E5.2																																				
	E5.3																																				
	E5.5																																				

Objectives

- To complete the experimental database on cryogenic LH2 combustion.
- To analyze experimental data in order to develop and validate existing or to generate new models for LH2 combustion.
- To develop empirical and semi-empirical engineering correlations for risk assessment and safety distances evaluation.
- The phenomena to be considered
 - LH2 jet fire behaviour, including scaling and radiation properties
 - Burning LH2 pool behaviour, radiation characteristics
 - Cryogenic hydrogen combustion in a layer geometry relevant to flame spread over the spill of LH2
 - Flame acceleration and DDT for cryogenic hydrogen-air clouds in an enclosure.
 - BLEVE
- The major characteristics to be investigated should be the pressure, temperature, heat flux, and dynamics of the processes. Effects of scale and turbulence should also be considered as parameters of the processes. Similar to LH2 distribution the combustion analysis shall include confinement geometry and obstructions.

Simulations

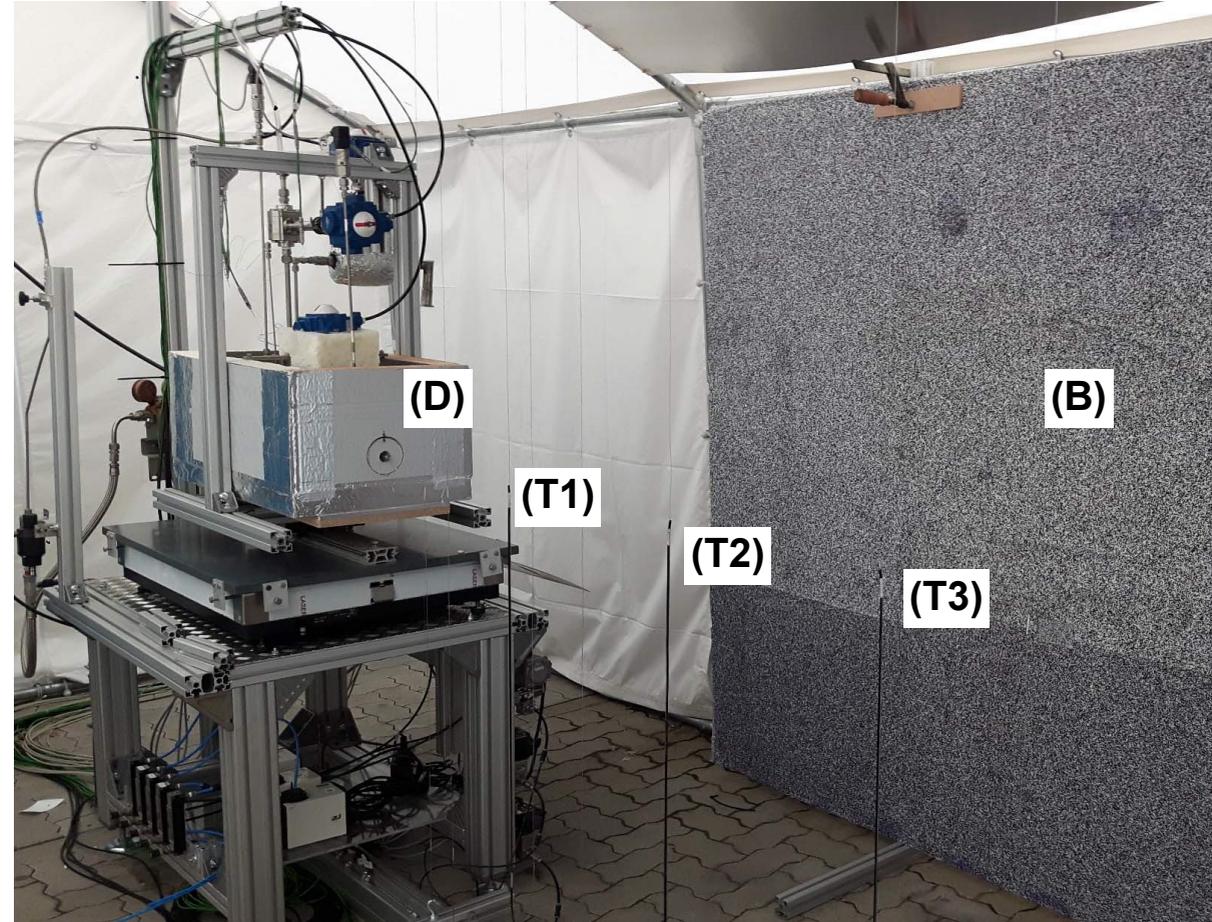
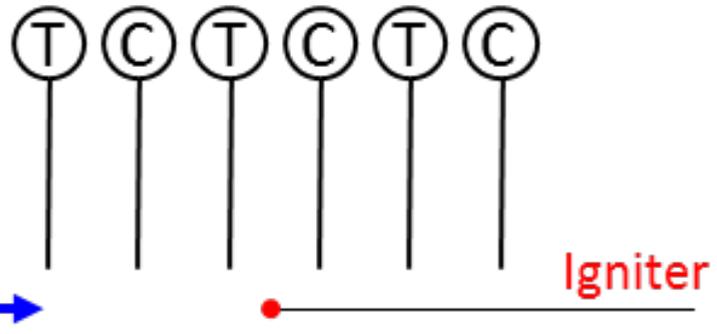
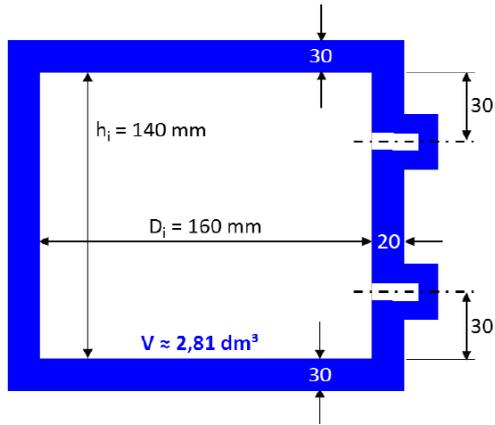
- Simulations to be done
 - The development of numerical models based on the theory and recent experimental results
 - Pre-test (blind) simulations of all phenomena for cryogenic LH2 combustion
 - Validation against new combustion experiments and code improvement
 - Competitive comparison of numerical results between partners' simulations
 - Simulations of real accident scenarios relevant to LH2 combustion
 - Generation of simplified engineering correlations for safety analysis

Cryogenic hydrogen jet fire experiments (E5.1)

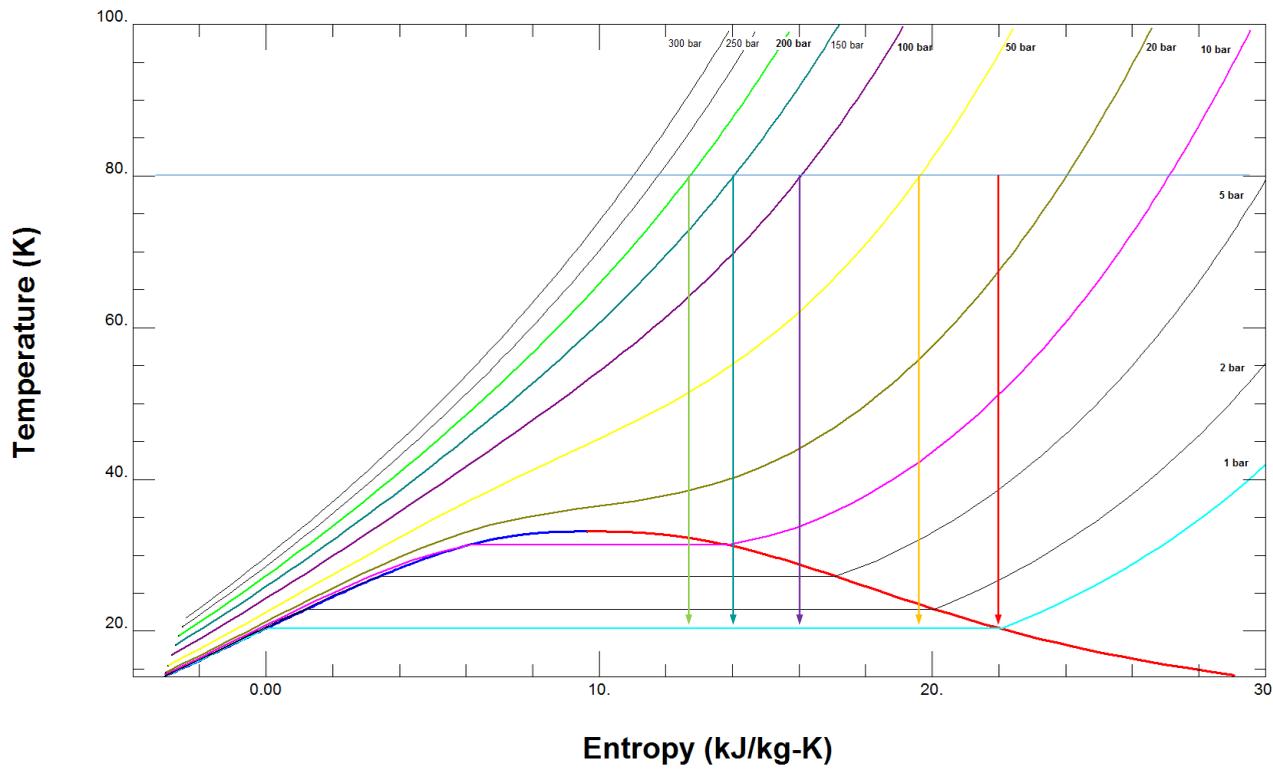


- Objectives
 - To close knowledge gaps and to generate the data for model validation on hazard distances due to pressure and heat radiation effects under delayed ignition of cryogenic hydrogen jet.
- Measurements
 - Pressure inside the tank (1 sensor)
 - Temperature inside the tank (3 thermocouples)
 - Distant pressure (3-5 sensors)
 - Heat flux (2-3 sensors)
 - Axial temperature along ignited jet (5-10 sensors)
 - A high speed video combined with BOS technique (2-3 cameras)
- Variables
 - 2 initial temperatures (300K, **80K**)
 - 3 bulk pressures within the range 5-200 bar
 - 3 nozzle diameters (1, 2, 4 mm)
 - 5 ignition locations (0-2 m)
 - 4 time delays (0-1 s)

Experimental layout 1



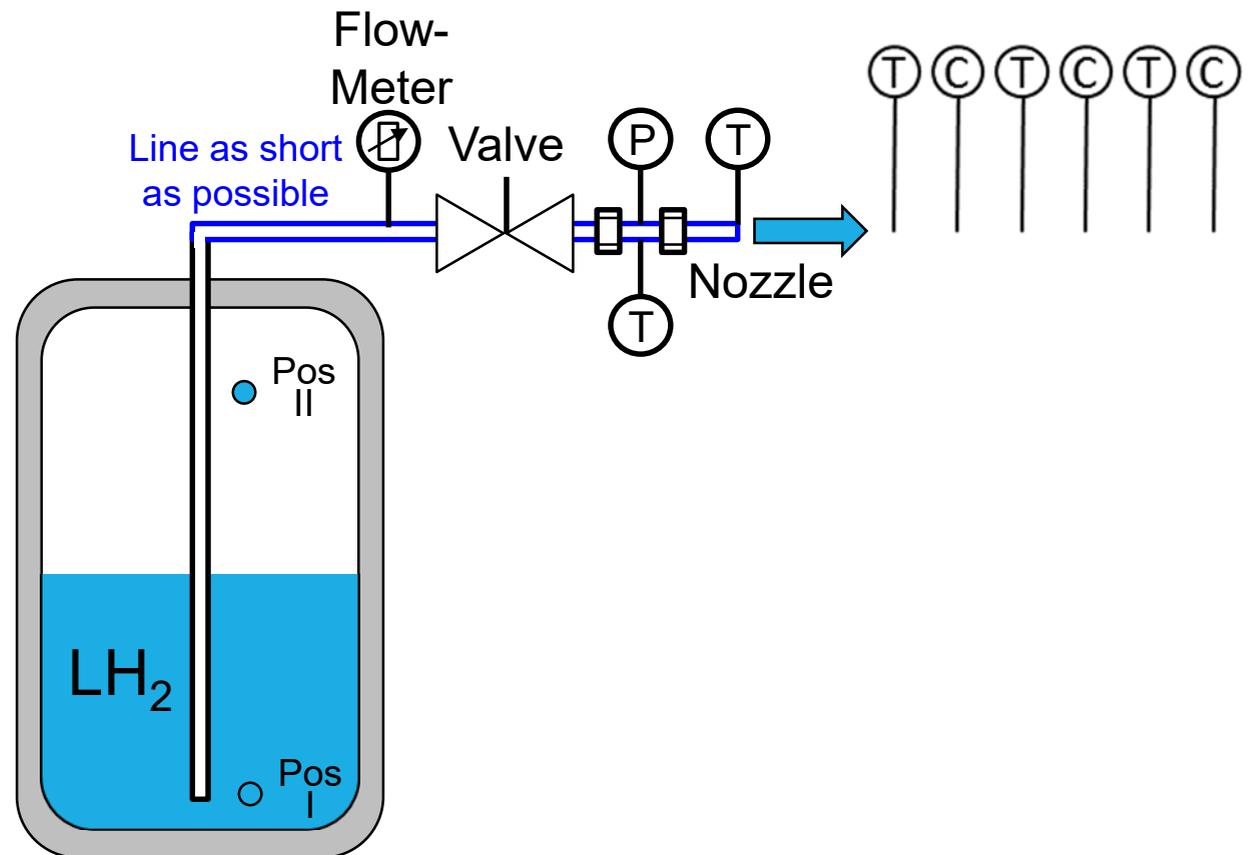
T-S diagram of state of hydrogen



T (K)	P (bar)	Density (kg/m ³)	Sound Speed (m/s)	H2 inventory (g)	Characteristic release time (s)			
					Nozzle diameter (mm)			
					0.5	1	2	4
300	200	14.4	1493	41.3	9.78	2.45	0.61	0.15
300	150	11.1	1448	31.9	10.1	2.52	0.63	0.16
300	100	7.6	1404	21.9	10.4	2.60	0.65	0.16
300	50	3.9	1361	11.3	10.7	2.68	0.67	0.17
300	20	1.6	1335	4.6	10.9	2.73	0.68	0.17
					0.5	1	2	4
80	200	48.2	1207	138.3	12.1	3.03	0.76	0.19
80	150	40.5	1065	116.1	13.7	3.43	0.86	0.21
80	100	29.9	917	85.6	15.9	3.98	1.00	0.25
80	50	15.7	792	45.0	18.4	4.61	1.15	0.29
80	20	6.2	747	17.8	19.5	4.89	1.22	0.31

Cryogenic jet fire experiments (E5.1)

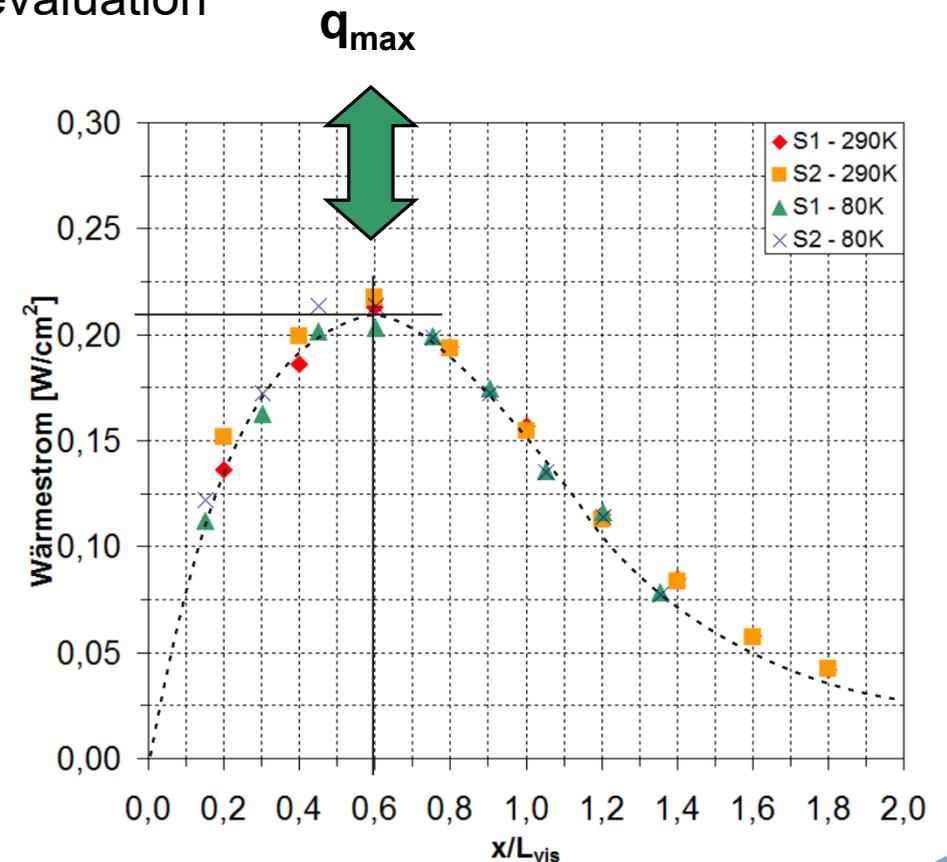
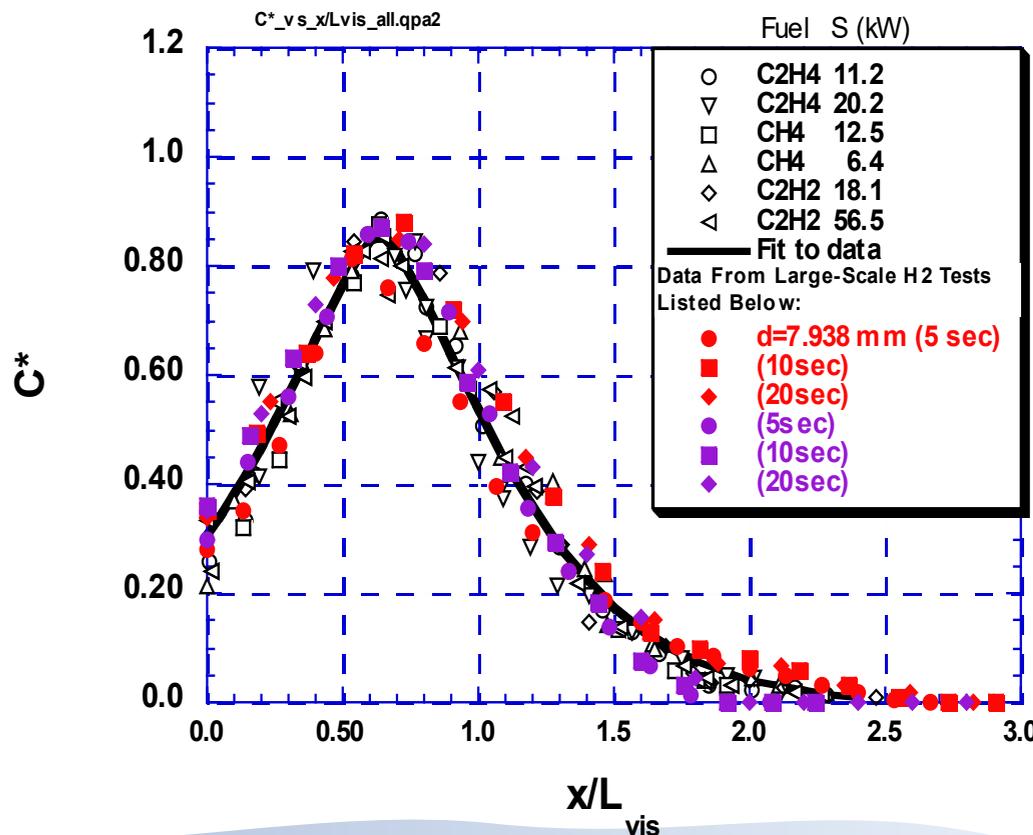
- For the ignited experiments an ignition device will be added to the existing facility
- Selected experiments of the unignited series will be repeated with ignition
- Parameters to be varied include:
 - Mass flow rate (bulk pressure)
 - Nozzle diameter
 - Ignition position
 - Ignition delay time.



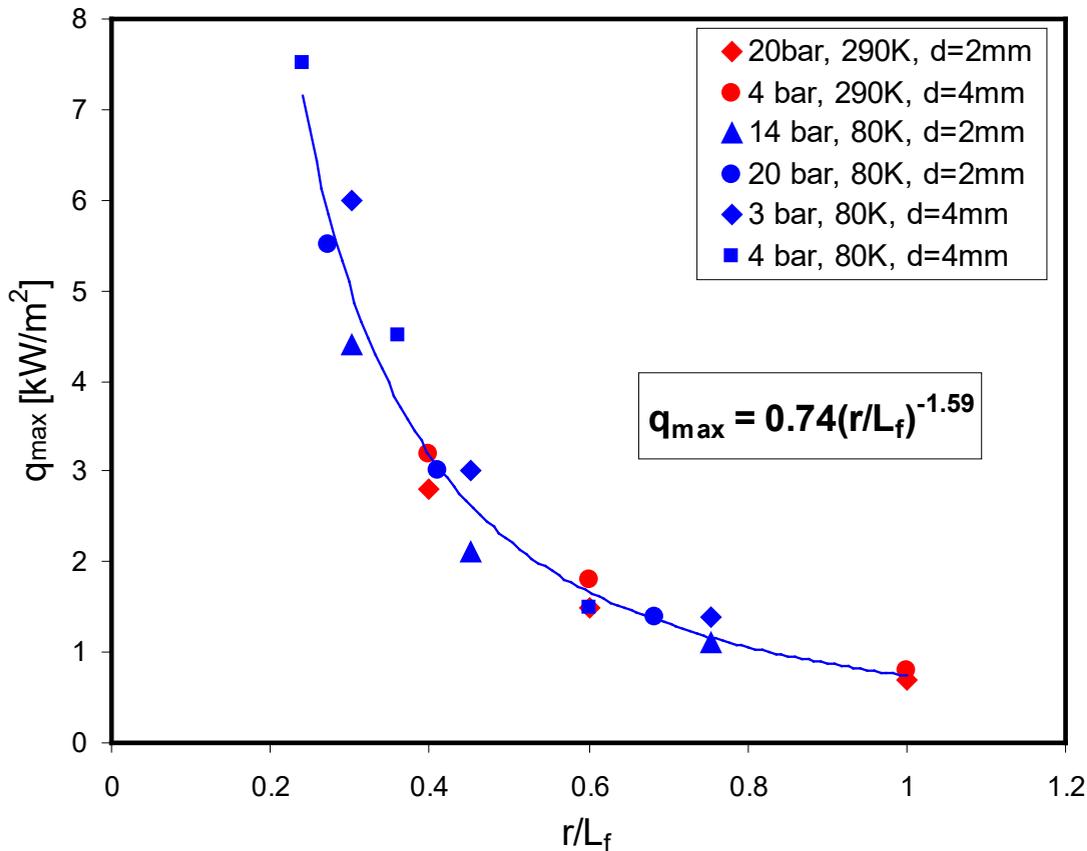
SCALING OF THERMAL MEASUREMENTS

T_0 [K]	d_0	p_0 [bar]	m [g/s]	$x_{Q_{max}}$ [m]	L_{vis} [m]
290	2	20	3,3	0,75	1,25
	4	4	3,3		
80	2	14	3,3	1	1,66
		20	4,4	1,1	1,83
	4	3	3,3	1	1,66
		4	4,4	1,25	2,08

- Nice scaling of thermal properties even including the initial temperature effect. Behavior is similar to previous experimental data (Sandia Nat. Lab.)
- Maximum heat flux is the most important characteristic of burned hydrogen jet for conservative hazard evaluation



SCALING OF THERMAL MEASUREMENTS



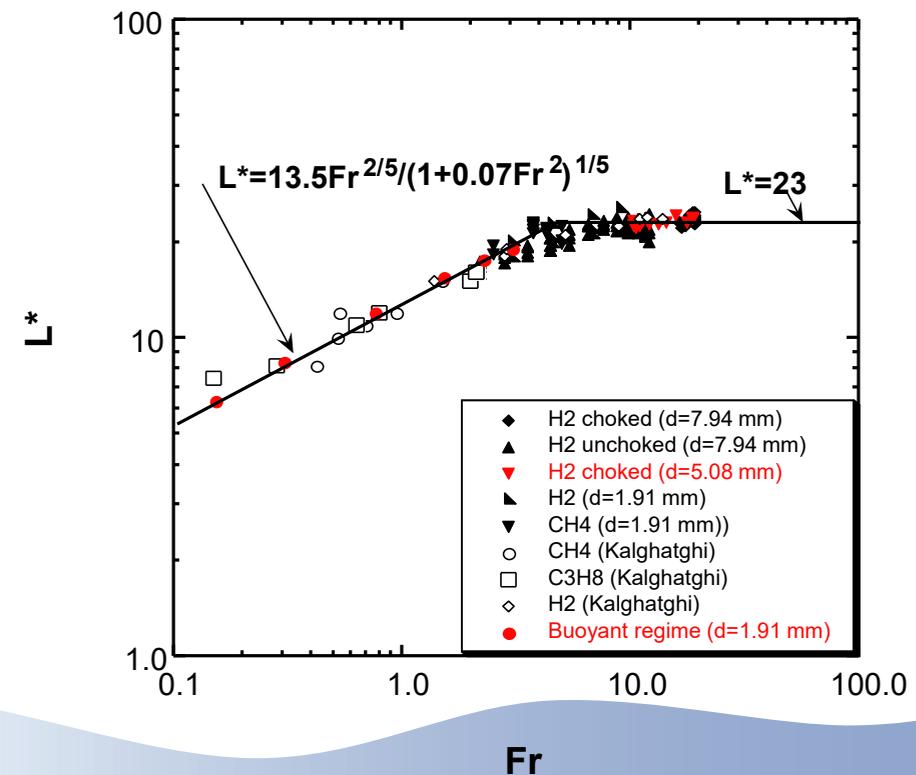
- All experimental data on maximum heat flux for different distances from jet axis r normalized by visible flame length L_f are collapsed in one curve
- For the same mixture and for high momentum jets the visible flame length L_f is rather simple function of nozzle diameter and hydrogen density in a pressurized volume:

$$L_f = 23 \cdot \frac{d}{f_s} \sqrt{\frac{\rho_e}{\rho_\infty}} \quad (Fr > 5)$$

- Using scale correlation for maximum heat flux:

$$q_{\max} = 0.74(r/L_f)^{-1.59}$$

we can evaluate the safety distance for given level of critical heat flux corresponding, for instance, to pain limit or different burn degree for human skin



HEAT RADIATION OF HYDROGEN JET

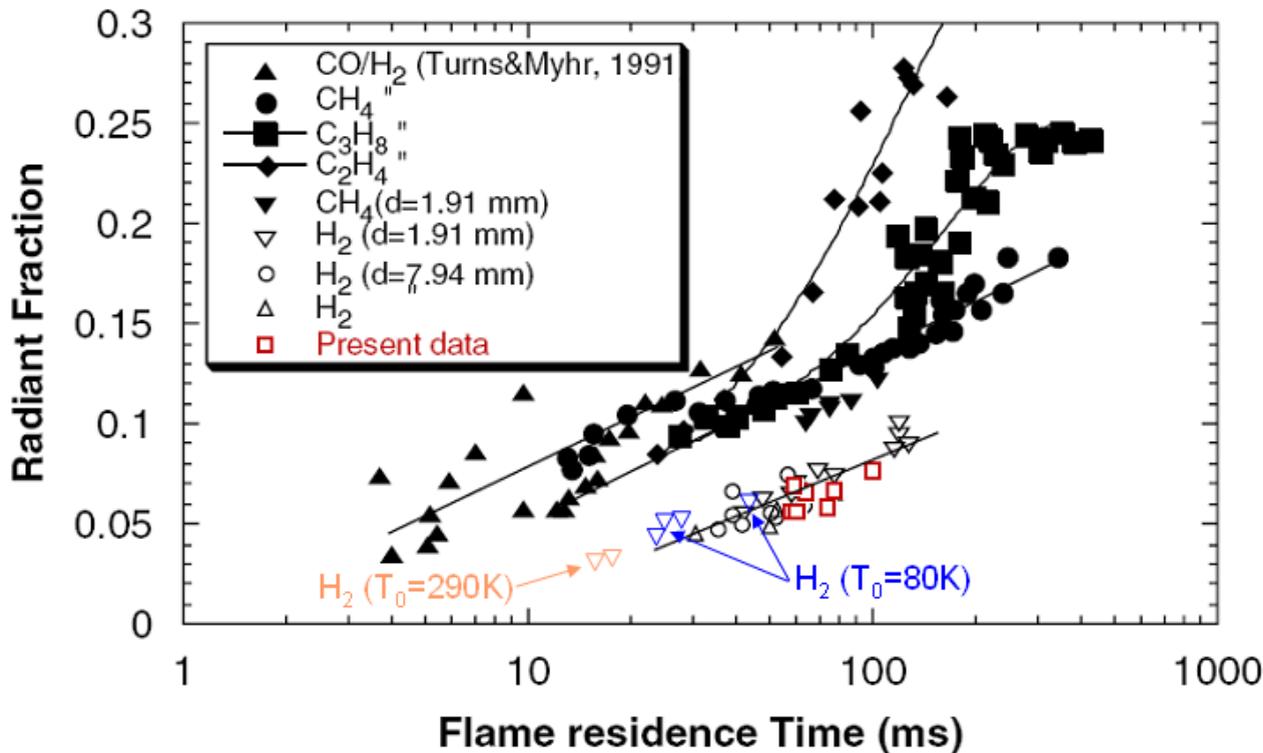


$$X_{rad} = \frac{S_{rad}}{m \cdot \Delta H_C}$$

$$X_{rad} = \frac{S_{rad}}{m \cdot \Delta H_C} = \frac{Q_{max} \cdot O_{Zylinder}}{m \cdot \Delta H_C} = \frac{Q_{max} \cdot 2\pi \frac{L_{vis}}{2} \left(L_{vis} + \frac{L_{vis}}{2} \right)}{m \cdot \Delta H_C}$$

X_{rad} : Radiant fraction
 S_{rad} : Total thermal energy
 m : Mass flow rate
 ΔH_C : Enthalpy of reaction

T_0 [K]	d_0	p_0	m	L_{vis} [cm]	X_{rad}
290	2	20	3,3	125	0,032
	4	4	3,3	125	0,032
80	2	14	3,3	166	0,056
		20	4,4	183	0,051
	4	3	3,3	166	0,056
		4	4,4	208	0,066



- Typical values of radiant fraction are:
 $X_{rad} = 0.03$ for 290K
 $X_{rad} = 0.06$ for 80K
- Radiant fraction depends on jet scale but residence time as a measure of scale is not convenient for practical purposes:

$$T_f = \frac{(\rho_f W_{vis}^2 L_f f_s)}{(3\rho_0 d_J^2 u_J)}$$

- Visible flame length can be used for scaling

Thermal hazards CFD modelling

UU WiP on KIT cryogenic hydrogen jet fire tests

The CFD approach previously validated against SNL cryogenic ignited releases is employed to model the horizontal jet fire tests performed in KIT with release conditions:

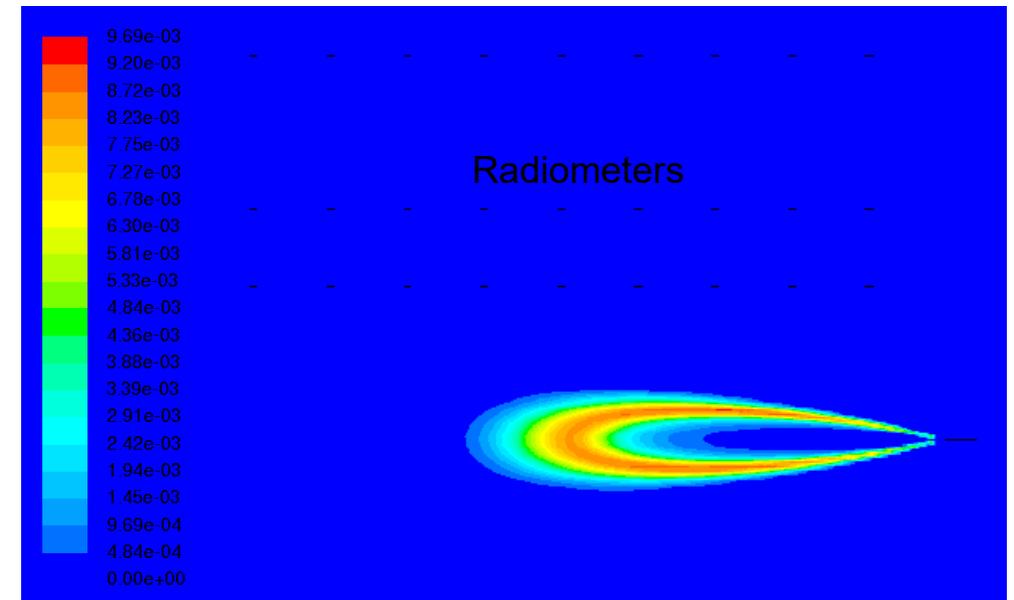
- P=3-20 bar
- T=80 K
- d=2 mm and 4 mm

Preliminary tests on the effect of:

- Humidity
- Ventilation system parameters

Aim of the study:

- Prediction of radiative heat flux aside the jet fire
- Prediction of flame length and calculation of associated hazard distances for horizontal releases

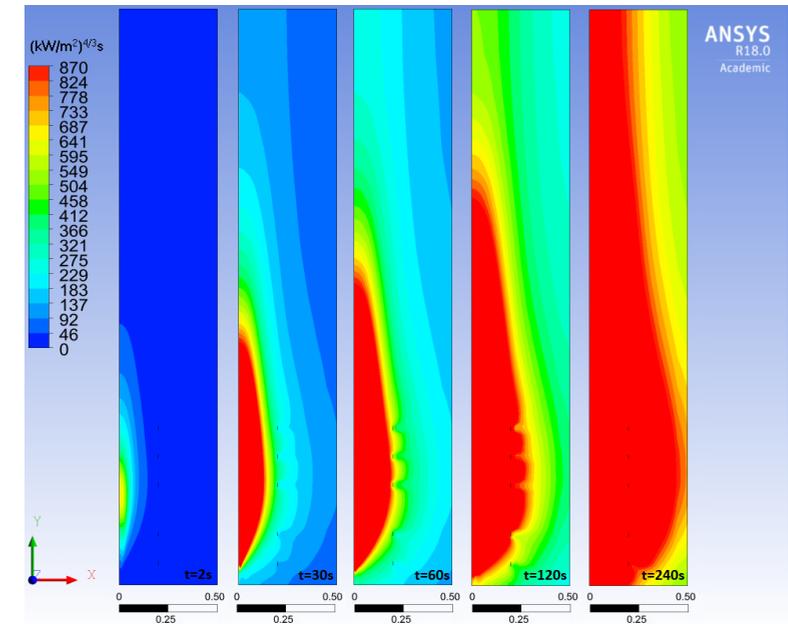


Preliminary results on OH mole fraction distribution – top view

Cryogenic hydrogen jet fires (UU)

Thermal dose calculation

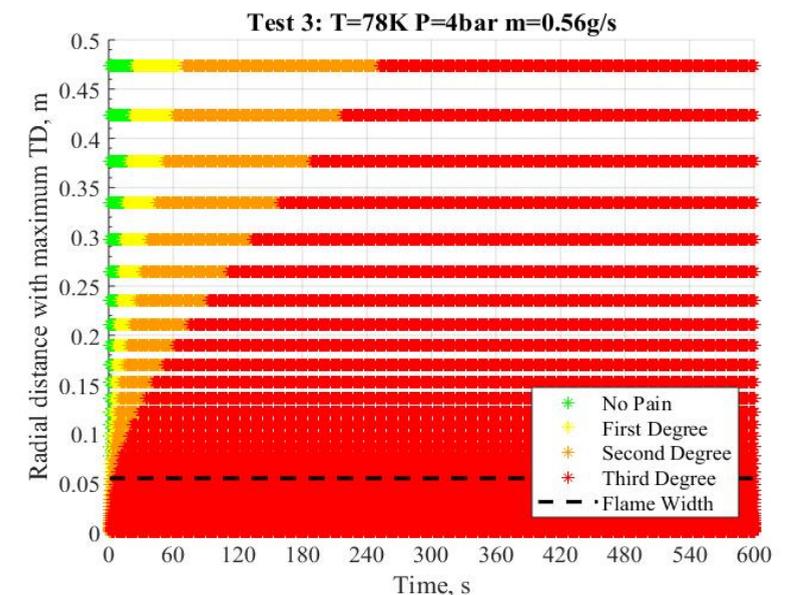
The employed CFD model has been previously validated against experiments by SNL on cryogenic hydrogen fires from storage with pressure up to 5 bar abs and temperature in the range 48-82 K.



Operating conditions at the release

Test No.	T, K	P, bar abs	d, mm	ṁ, g/s
1	64	2	1.25	0.33
2	48	2	1.25	0.38
3	78	4	1.25	0.56

Thermal dose distribution for Test 3

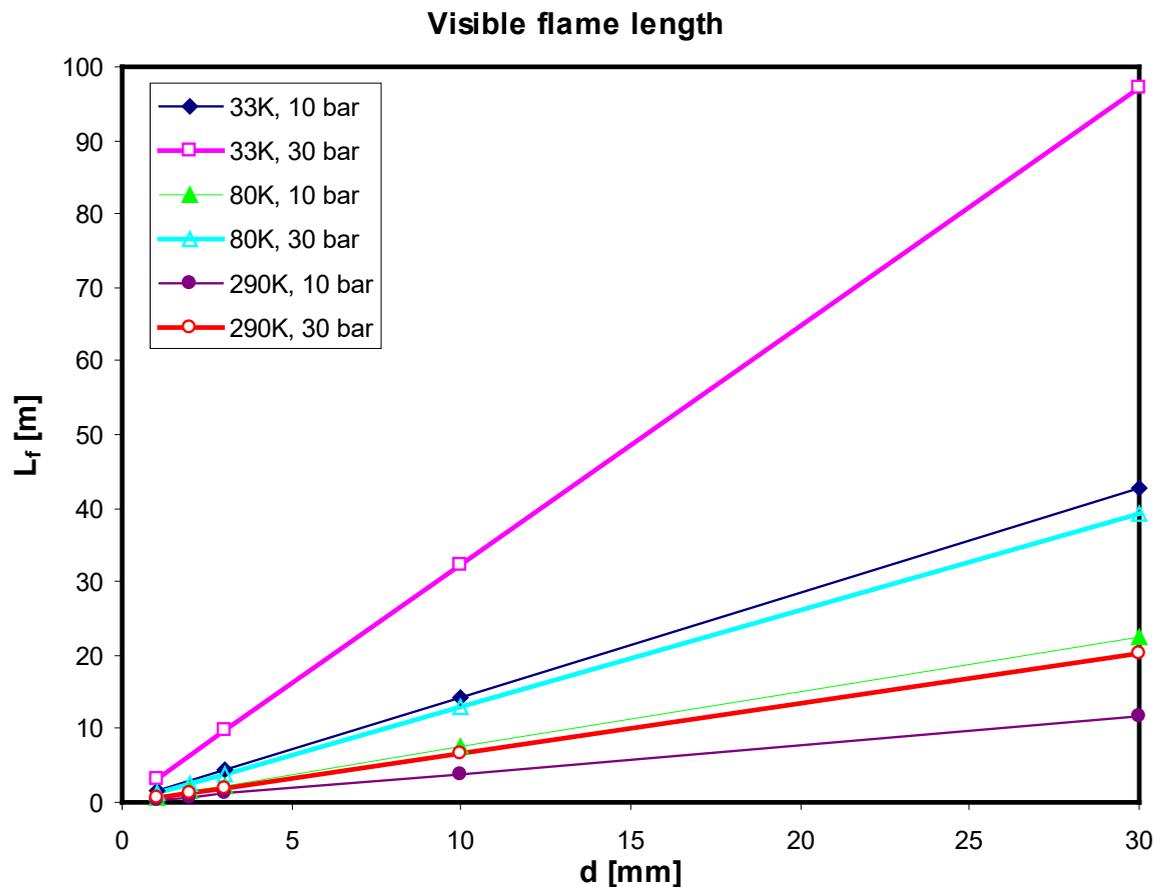
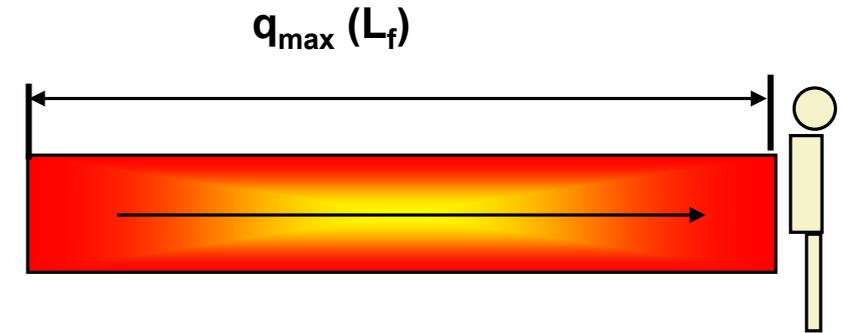
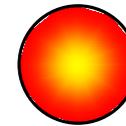


Burn Severity	Threshold Dose for infrared radiation, $(\text{kW}/\text{m}^2)^{4/3}\text{s}$
First degree	80-130
Second degree	240-730
Third degree	870-2640

Thermal dose harm levels: time versus radial distance with max TD for Test 3

SAFETY DISTANCES

- Side view area $S = 0.17L_f^2$
- Axial view area $S = 0.02L_f^2$
- As a safety distance for axial position visible flame length can be used L_f

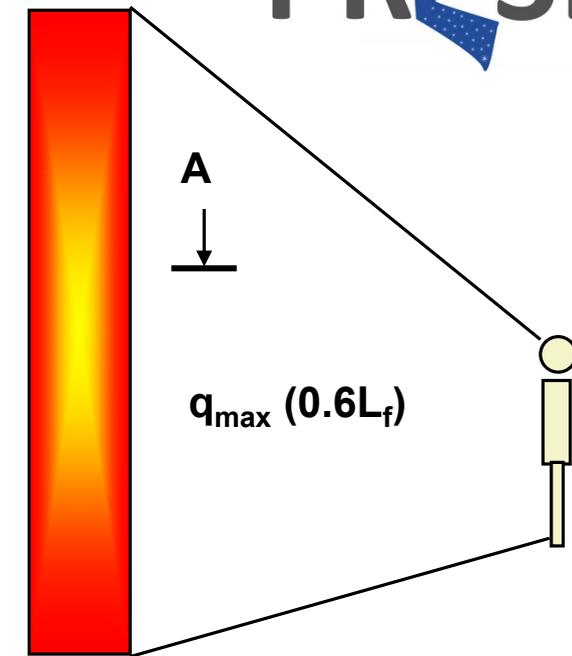
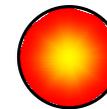


- Maximum radiation reached at safety distance equal to L_f
- Visible flame length L_f increases with nozzle diameter and pressure increase and decreases with initial temperature increase

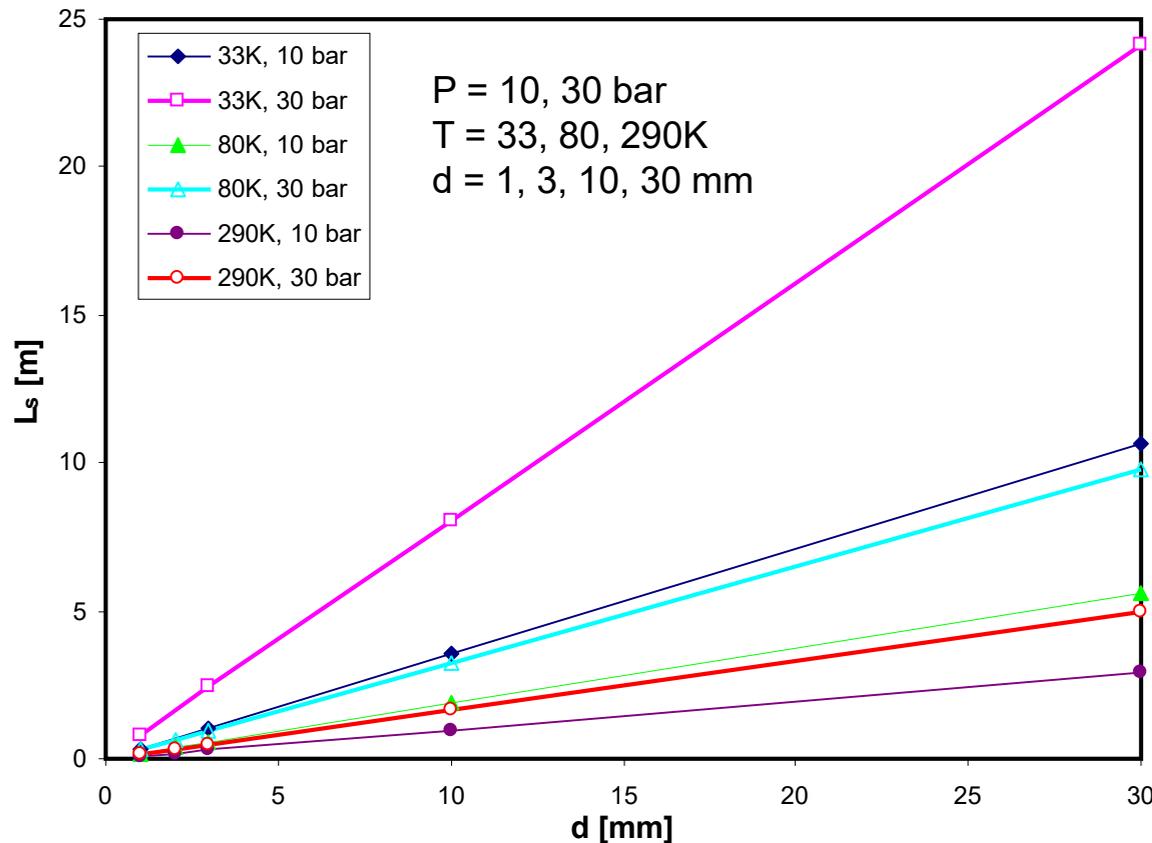
SAFETY DISTANCES

- Side view area $S = 0.17L_f^2$
- Axial view area $S = 0.02L_f^2$
- As a safety distance for axial position visible flame length L_f can be used

A-A

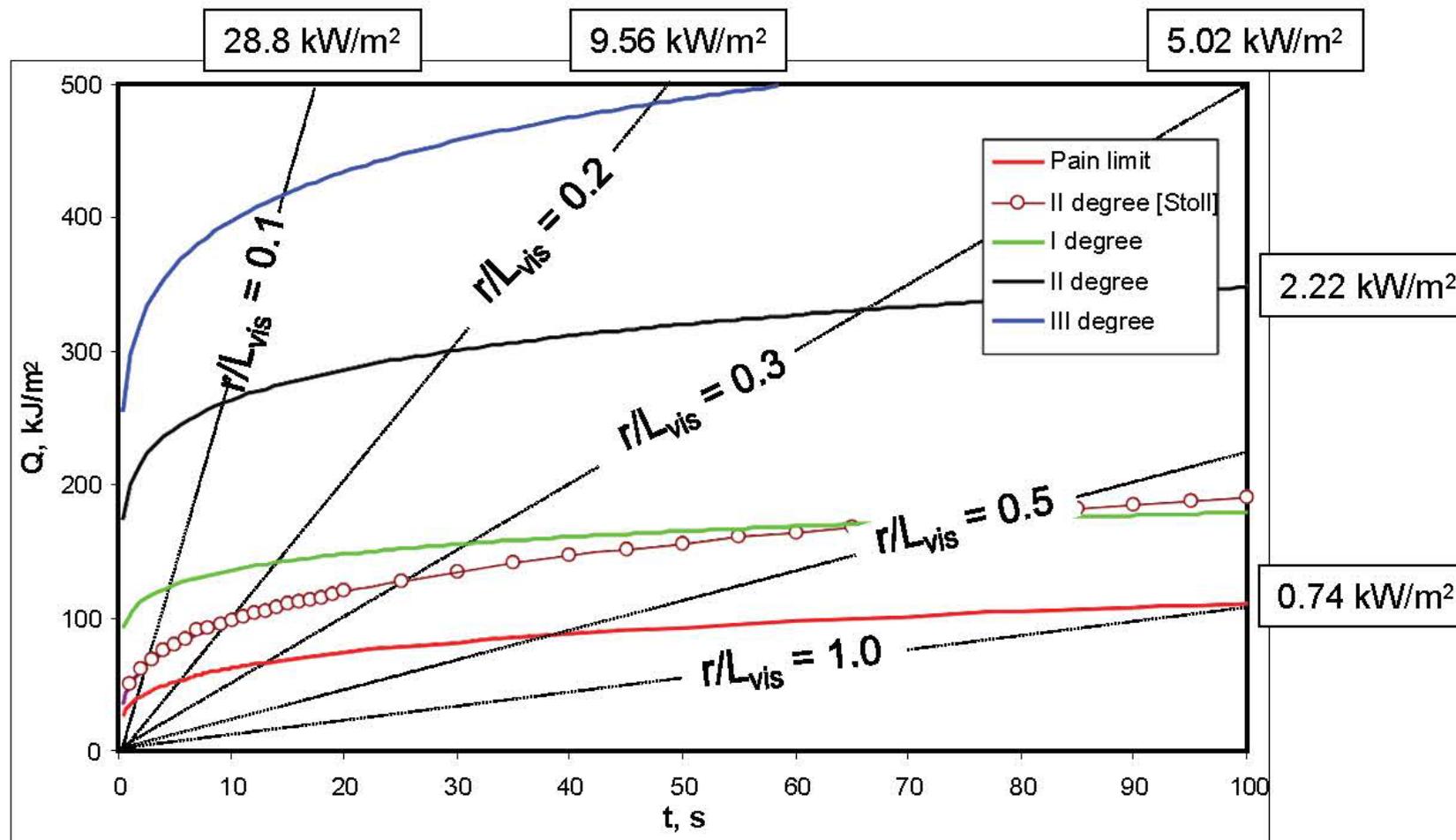


Safety distances (pain limit)= first degree



- Safety distances calculated for pain limit at exposure (10 sec)
- Maximum radiation reached at safety distance in the point $0.6L_f$
- Safety distance increases with nozzle diameter and pressure increase. It decreases with initial temperature increase

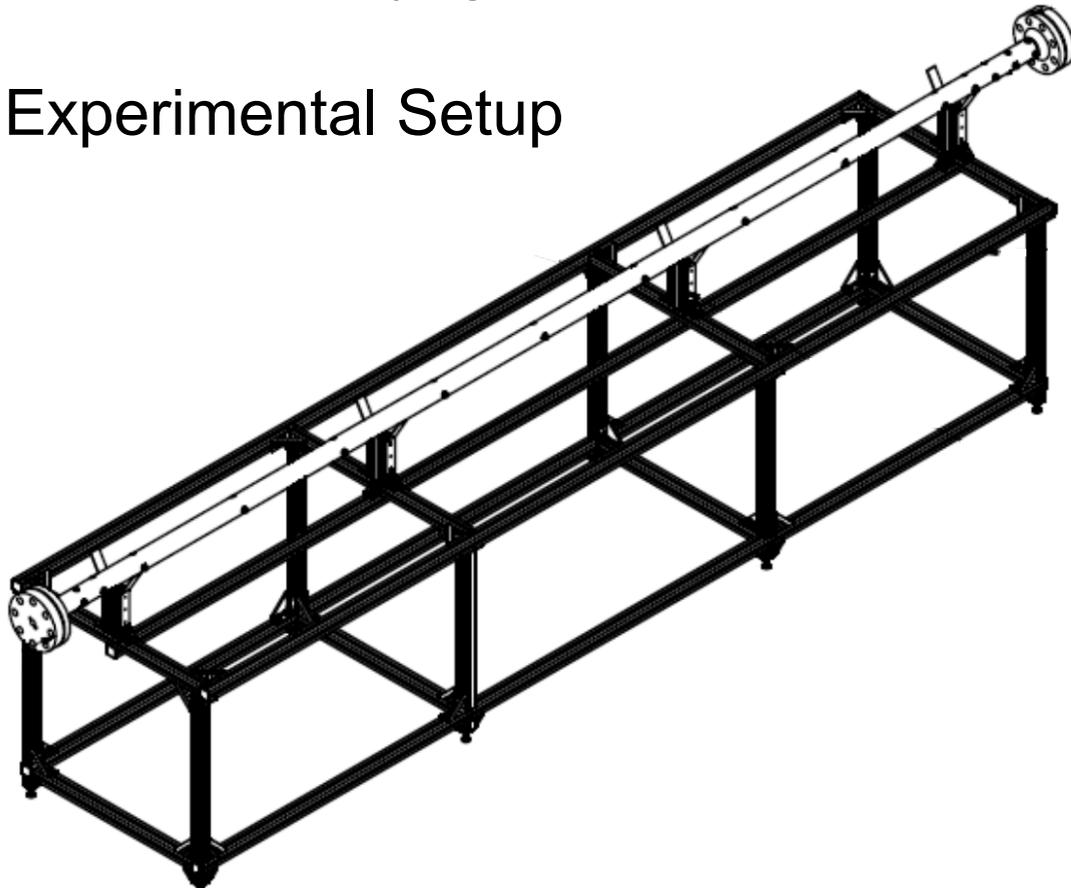
Damage diagram



Maximum exposure times for different degrees of skin damage from thermal radiation of turbulent hydrogen gas jet flames

E5.2: Combustion-Tube-Facility

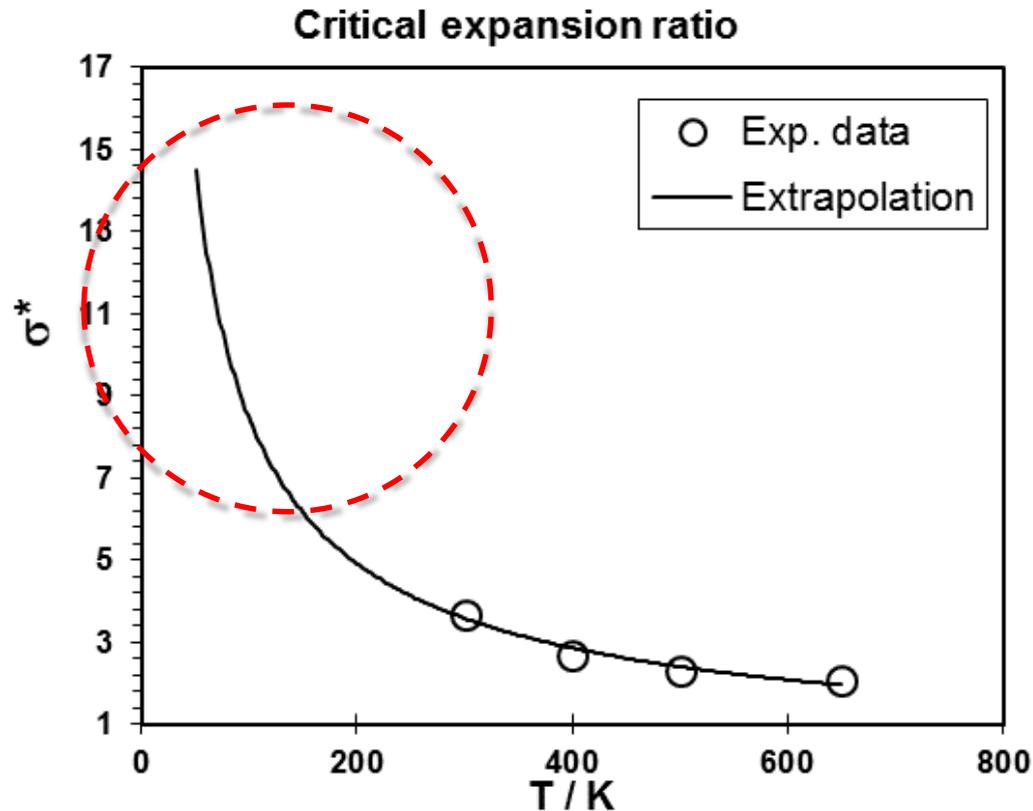
- The critical conditions for flame-acceleration and DDT for Hydrogen-Air-Mixtures at cryogenic temperatures will be investigated
- Experimental Setup



- Facility installed to a tent with removable sides in the free field behind main hall of HYKA,
- Control units in a container besides the facility.

Prediction of the results

Critical expansion ratio for an effective flame acceleration



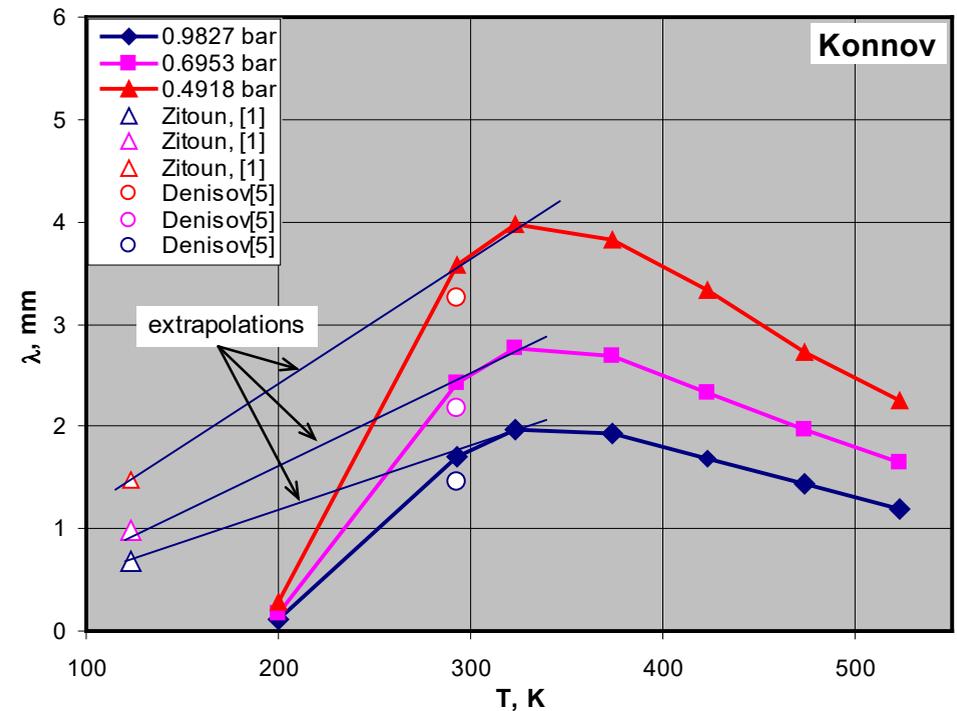
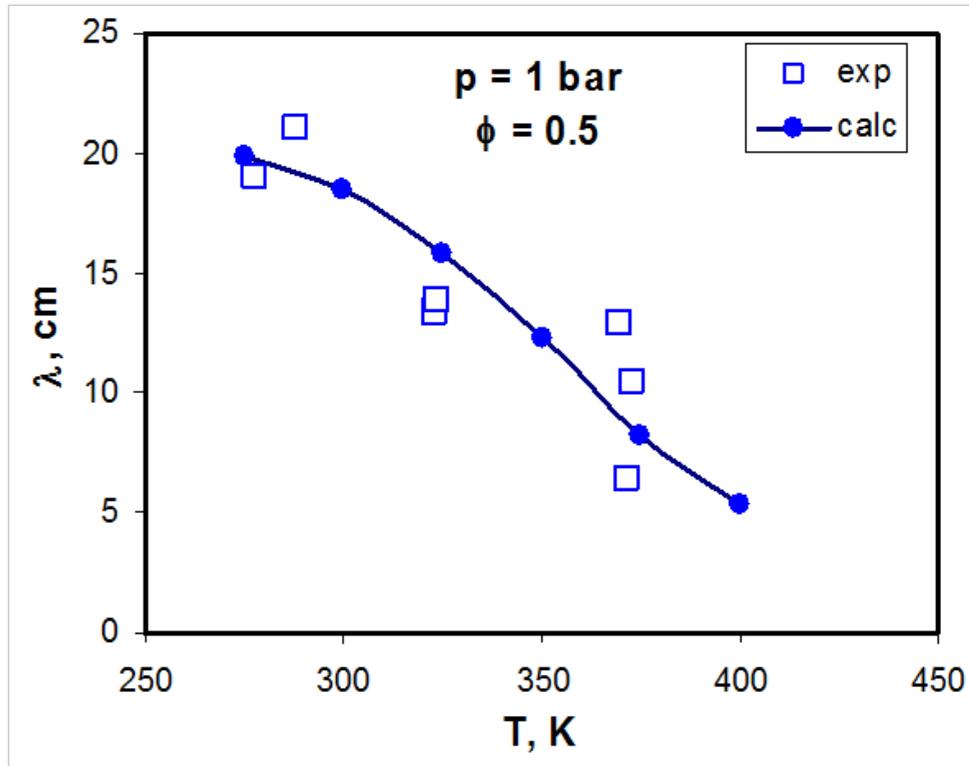
T, K	C _{H2} , %mol	σ*
300	11	3.75
200	10.34	4.92
150	10.09	6.14
100	9.58	8.49
78	9.13	10.67
50	8.60	13.89

- Lack of fundamental data on combustion properties at cryogenic temperatures
 - ➔ Too far extrapolation to be properly predicted
 - ➔ Cannot be theoretically predicted up to now
 - ➔ Experiments should be done

Prediction of the results

Detonation cell size (7λ criterion)

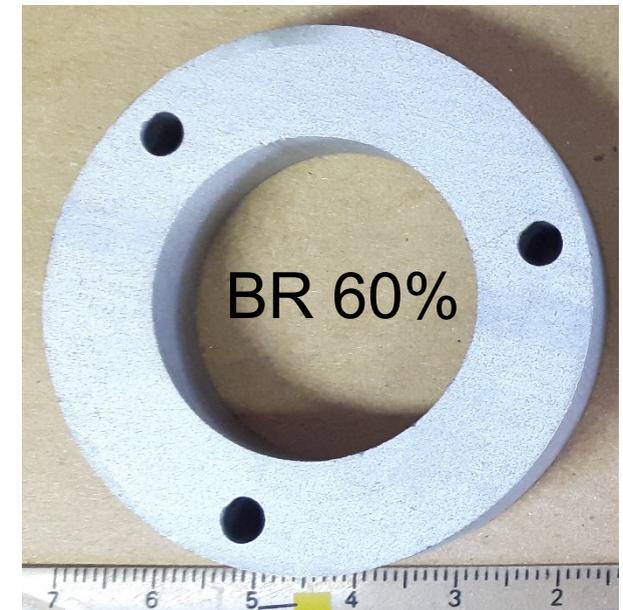
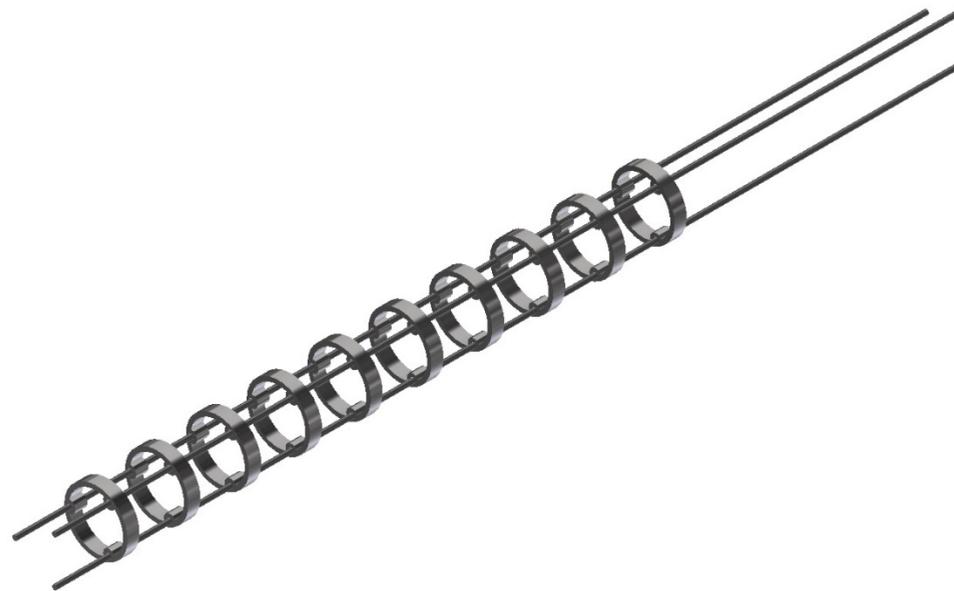
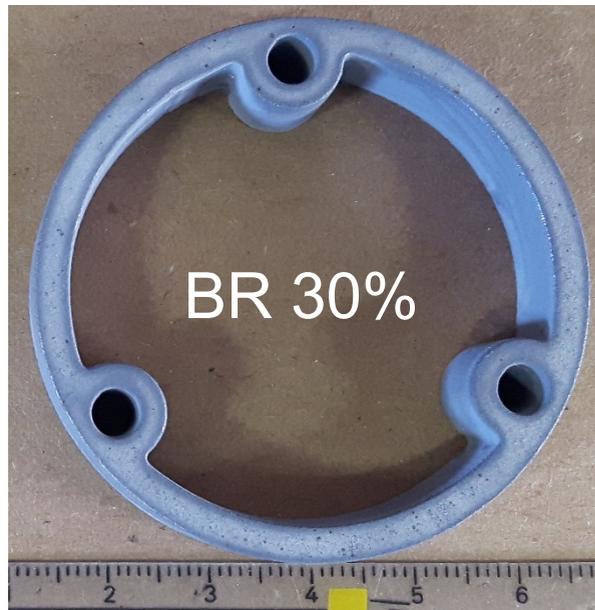
Hydrogen-air



- Lack of fundamental data on combustion properties at cryogenic temperatures
 - ➔ Too far extrapolation to be properly predicted
 - ➔ Experiments should be done (sooted plates technique)

E5.2: Combustion-Tube-Facility

- Obstacles



- 54 mm id, 10-mm wall thickness and 5-m long
- 2 different obstacles (BR 30% and BR 60%),
- obstacles will be positioned evenly along the complete tube length (spacing: 1 inner diameter of tube) via three thin threaded rods,
- obstacles were manufactured externally (already delivered).

Combustion-Tube-Facility

■ Test Parameters

- 2 temperatures in the range 70 K to 100 K,
- 2 blockage ratios (30% and 60%)
- 10 H₂-concentrations within the ranges
 - 6 to 12 Vol.% H₂ (for σ^* evaluation)
 - 15 to 20 Vol.% H₂ (for λ evaluation)
 - 30 Vol.% H₂ (for λ evaluation)
 - 60 to 75 Vol.% H₂ (for λ evaluation)

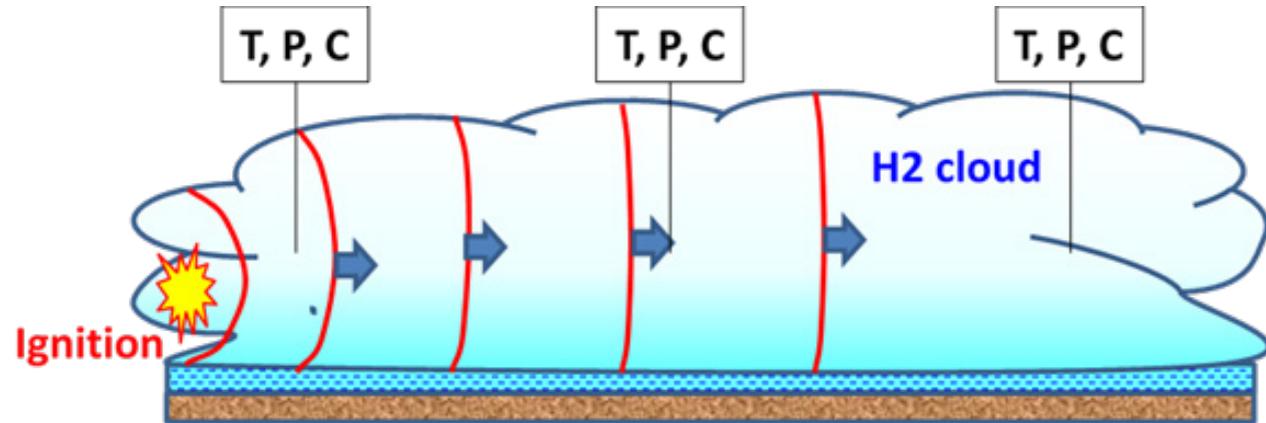
Flame propagation over a spill of LH2 (E5.3)



- Objectives
 - To evaluate a danger of flame propagation over a spill of LH2 in presence of inverse vertical hydrogen concentration gradient at cryogenic.
- Measurements
 - Local hydrogen concentration (an array 5x6 units)
 - Vertical temperature profile (3-5 thermocouples)
 - Dynamic pressure sensors (5 sensors)
 - Photodiodes (10 sensors)
 - Ion probes (10 sensors)
 - Axial temperature along the system (5-10 sensors)
 - A high speed video combined with BOS technique (2-3 cameras)
- Variables
 - 3 hydrogen concentration gradients
 - 3 layer thicknesses
 - 3 blockage ratios (0, 30 and 60%)

Pool-Facility

- Experimental set-up



- It seems to be difficult to generate a pool of LH2 with a surface of 1 m² with a reasonable budget for the enormous amount of LH2 that has to be spilled.
- If the pool is generated the atmosphere around it will consist of gaseous H2 with traces of other gases

The decision could be to provide the same conditions as above the LH2 spill. We just need to provide the same hydrogen concentration and temperature profile as for predefined LH2 evaporation rate.

Equilibrium temperature of LH2-air mixture

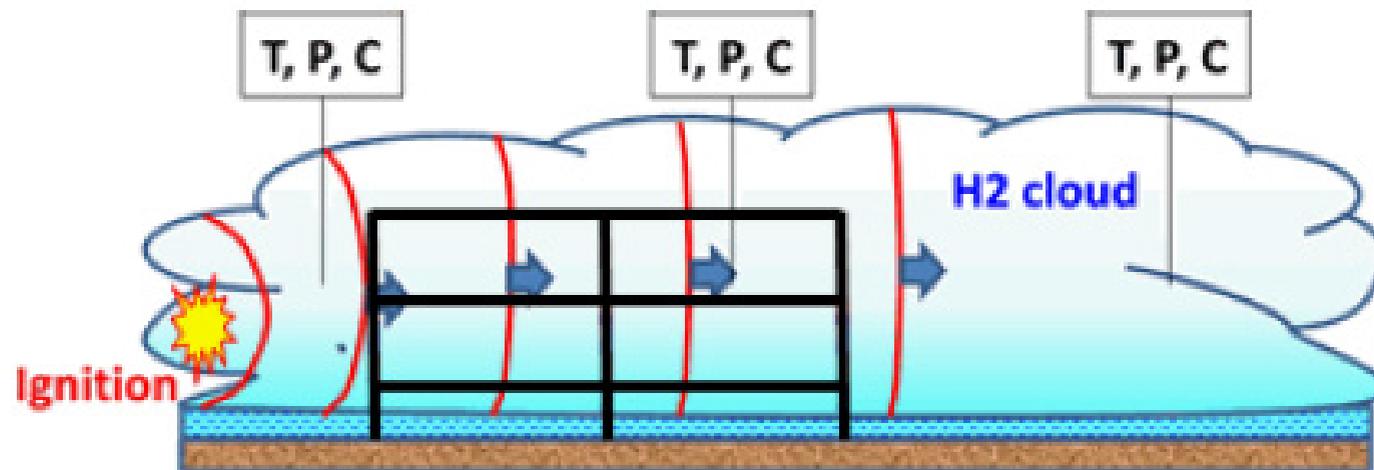


Hydrogen %v/v	Temperature °C	Temperature K
4	-0.12	273.1
10	-15.6	257.6
15	-28.5	244.7
20	-41.4	231.8
25	-54.5	218.7
30	-67.6	205.6
35	-80.9	192.3
40	-94.3	178.9
45	-107.9	165.3
50	-121.7	151.5
55	-136	137.2
60	-150.6	122.6
65	-165.9	107.3
70	-181.9	91.3
75	-197.9	75.3

So that it will be a gradient of hydrogen concentration and temperature as well. Within the flammability limits the temperature changes from 273K(LFL) to 75K(UFL). 206K corresponds to stoichiometric hydrogen concentration.

E5.5 LH2 Combustion with congestion/confinement variation (HSL) ('realistic' scenario)

- This option has more variables such as concentration and temperature of gas within congestion
- Congestion rig will be left open as heat will be removed immediately by surrounding air and structure in an enclosed volume
- Biggest challenge will be ensuring ignition due to variability from wind effects



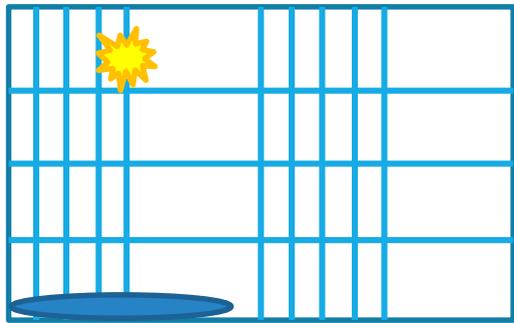
Experimental layout

- Size: 2 m * 3 m * 3 m = 18 m³
- Used in: Royle, M, Shirvill, LC, Roberts, T, Vapour cloud explosions from the ignition of methane/hydrogen/air mixtures in a congested region, International Conference on Hydrogen Safety. 11-18 Sept. 2007, San Sebastian, Spain. (PS/06/07)
- Potentially high noise levels so careful consideration needed
- This would provide a useful data comparison
- Could use a smaller congestion rig if this was an issue
- Also have a 1 m³ congestion rig for further obstruction

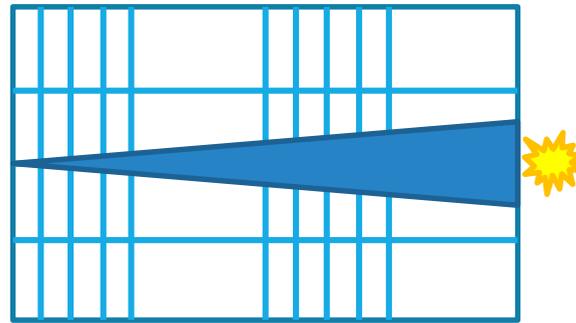


Experimental procedure

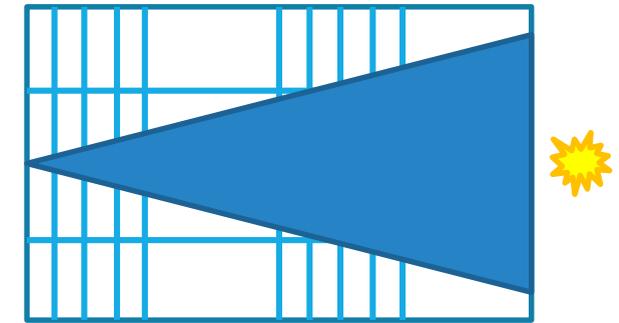
- Variables:
 - LH2 pool or jet
 - Congestion level
 - Confinement level
 - LH2 jet flow rate
- Ignition source located just downstream of rig to limit inventory of unburnt gas prior to entry into the congestion rig, this is to limit noise



Pool in congestion rig



Jet release into congestion rig



Higher flow rate release into rig, larger orifice

Test matrix



LH2?

m?

Blockage ratio?
(too small and too small difference)

Work Package	Experimental Subtask	Test No.	Gas	Pool/jet	Orifice size	Blockage ratio	Confinement
5	5.5	5.5.1	Hydrogen	Jet	¼"	1.25% (8 rows)	Open
5	5.5	5.5.2	Hydrogen	Jet	½"	1.25% (8 rows)	Open
5	5.5	5.5.3	Hydrogen	Jet	1"	1.25% (8 rows)	Open
5	5.5	5.5.4	Hydrogen	Jet	¼"	2.5% (15 rows)	Open
5	5.5	5.5.5	Hydrogen	Jet	½"	2.5% (15 rows)	Open
5	5.5	5.5.6	Hydrogen	Jet	1"	2.5% (15 rows)	Open
5	5.5	5.5.7	Hydrogen	Pool	1"	1.25% (8 rows)	Open
5	5.5	5.5.8	Hydrogen	Pool	1"	2.5% (15 rows)	Open
5	5.5	5.5.9	Hydrogen	Jet	¼"	1.25% (8 rows)	2 sides closed
5	5.5	5.5.10	Hydrogen	Jet	¼"	1.25% (8 rows)	2 sides closed

Instrumentation

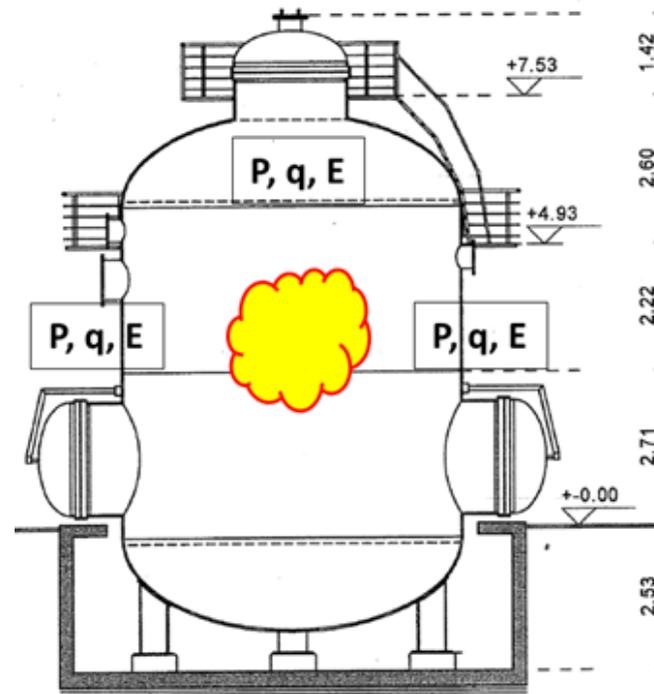


Instrumentation

- 2x blast pressure transducers at 5 m and 10 m from source, (ranged 0-2 bara, 500 kHz logging rate)
- 2x blast pressure transducers within congestion rig (ranged 0-5 bara, 500 kHz logging rate)
- Audible sound meters at 50 m and 100 m approximately
- Remote ignition system with multiple outputs, spark plugs and electrochemical igniters
- Thermocouples (16x co-located with vol% sensors and additional positions)
- Gas concentration measurement (vol% sensors within congestion rig, if thermocouples prove reliable in WP3 then no vol% sensors will be used)
- High speed video and IR

E5.4 BLEVE (KIT)

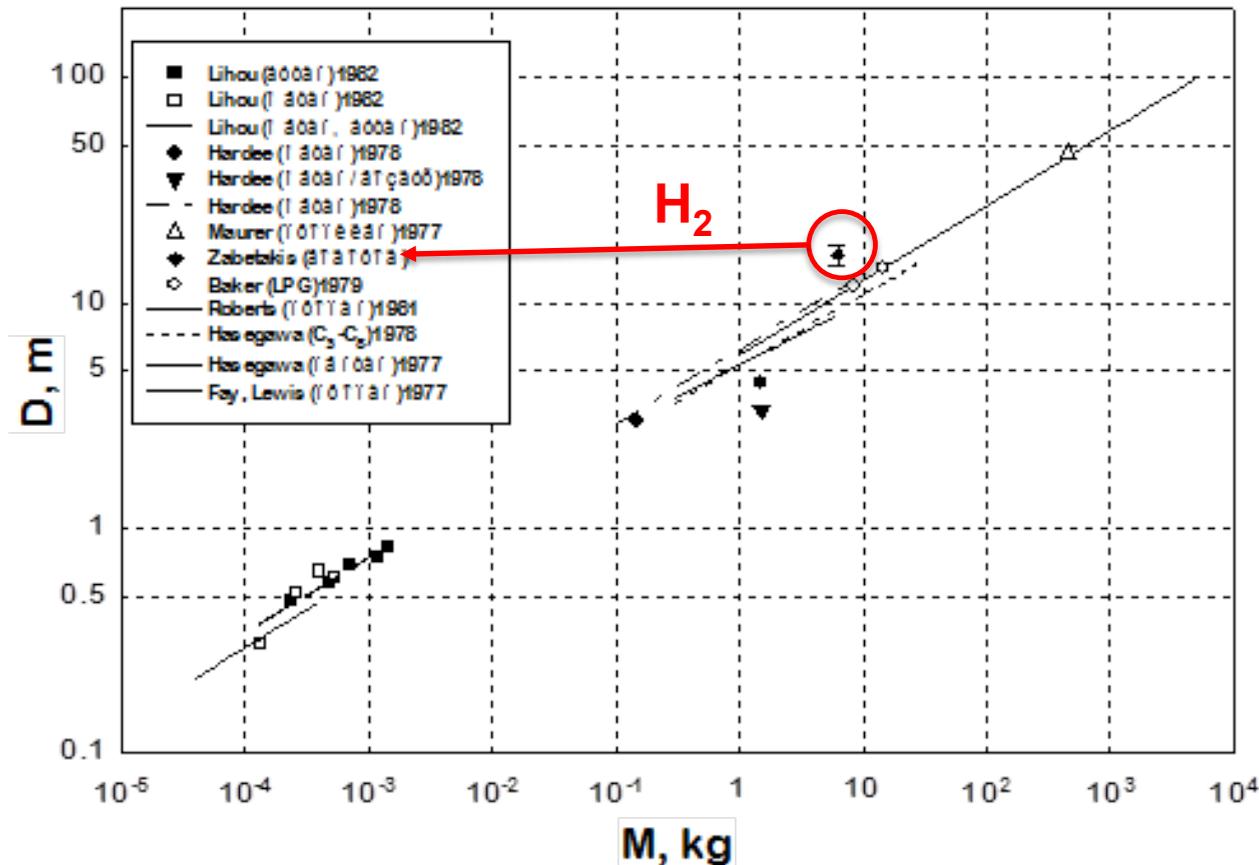
HYKA A2 ($V = 220 \text{ m}^3$)



- Experimental procedure
 - The tests will be performed inside the HYKA-A2 vessel (220 m³)
 - A pressurized liquid hydrogen inventory of different amount (<100 g) will be dispersed and ignited simultaneously
 - Initial pressure is not specified yet

Expected results

Maximum radius of fireball



$$D = 5.33 \cdot M^{0.327}$$

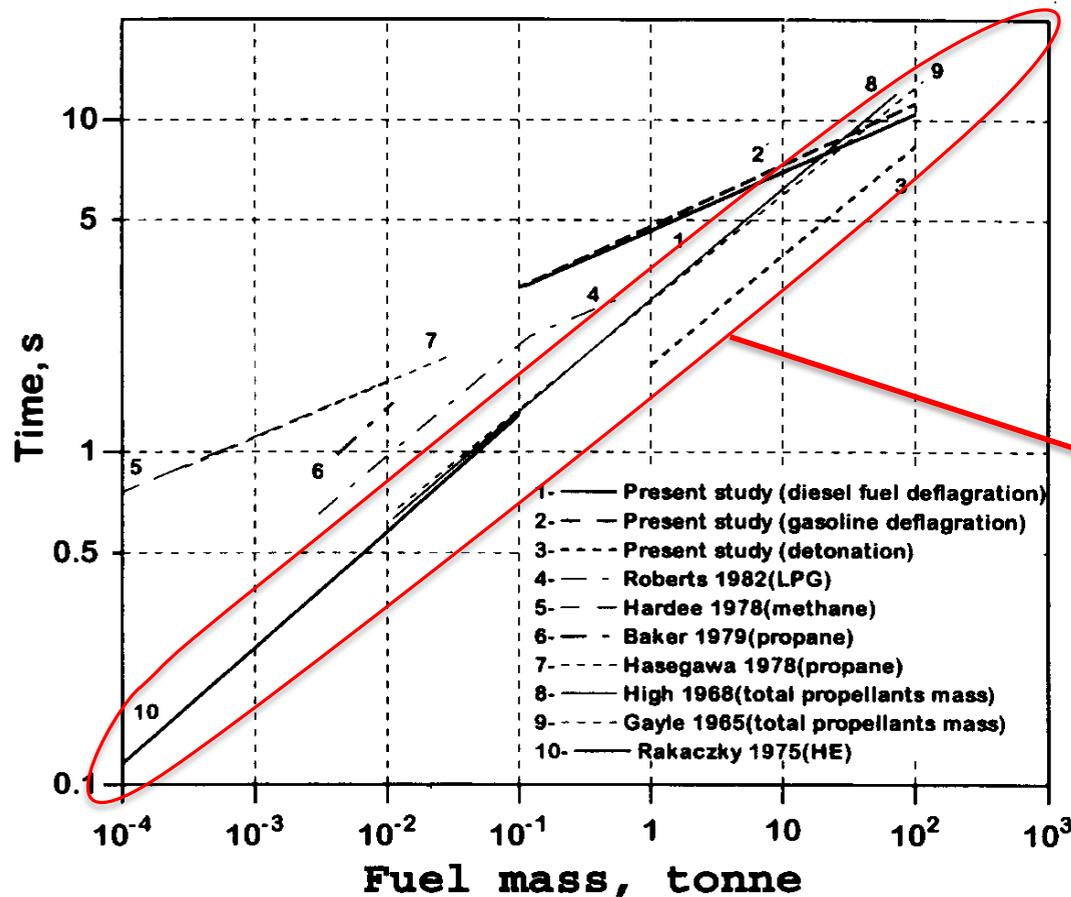
$$t_d = 0.45 \cdot M_f^{1/3}$$

$$E = 8.085 \cdot M_f$$

- Lack of fundamental data on hydrogen fireball characteristics at cryogenic temperatures
 - Behaves as BLEVE
 - Experiments should be done

Expected results

Characteristic time for fireball



$$R = A \cdot M^{1/3}$$

$$H = D \cdot M^{1/3}$$

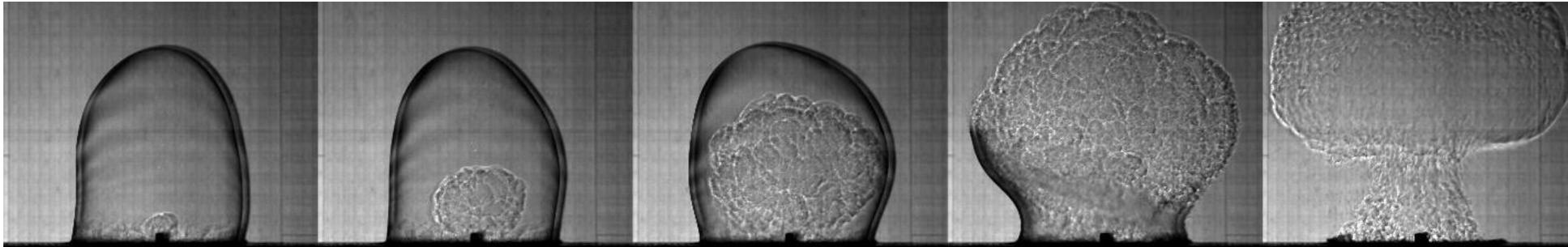
$$t = B \cdot M^{1/6}$$

BLEVE (Detonation, Sonic flames)

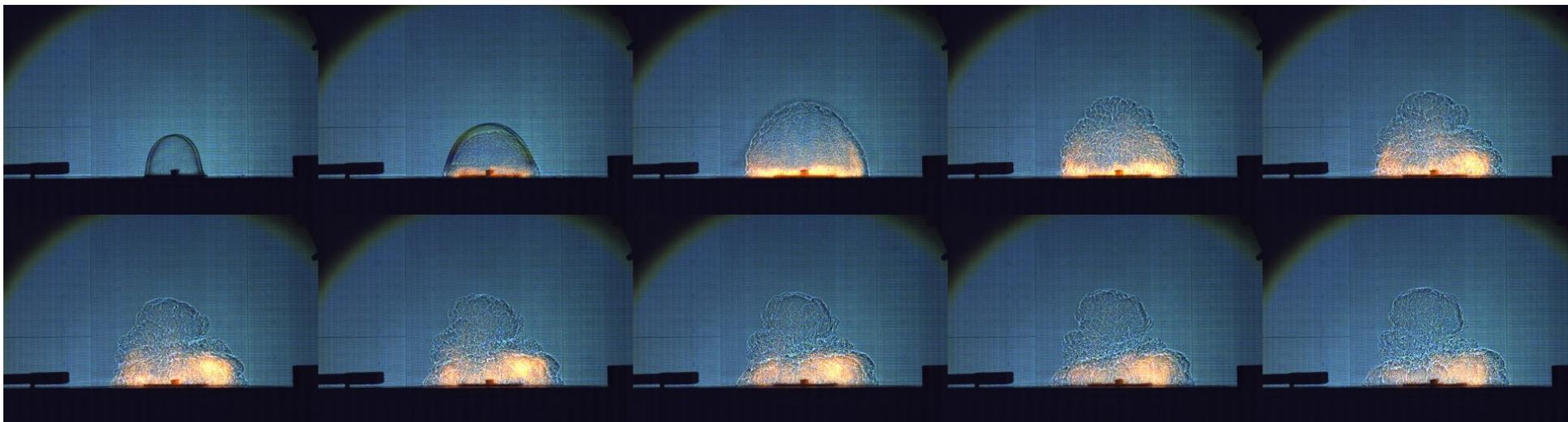
$$t = B \cdot M^{1/3}$$

- Lack of fundamental data on fireball characteristics at cryogenic temperatures
 - ➔ Behaves as BLEVE
 - ➔ Experiments should be done

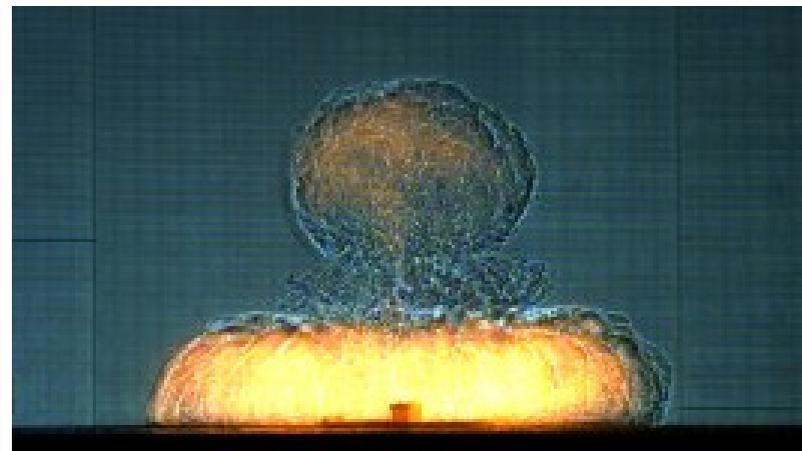
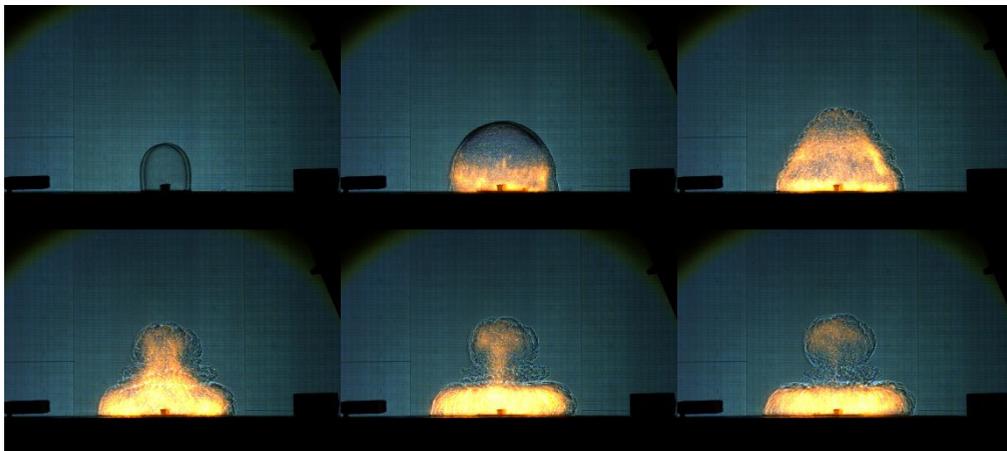
Preliminary tests in soap bubbles



10% H₂/air



40% H₂/O₂



50% H₂/O₂

Scale correlations

