PRESLHY

WP5 – Combustion

Paris, October 16-18, 2018

Pre-normative REsearch for Safe use of Liquid HYdrogen

KIT Karlsruher Institut für Technologie
Air Liquide
HEALTH & SAFETY LABORATORY
hySafe INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY
INERIS
ΔΗΜΟΚΡΙΤΟΣ
Pro-Science
Ulster University
WARWICK THE UNIVERSITY OF WARWICK

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	NCSRD	Pro-Science	UU
Person/months per participant:	6	4	4		4	12	4

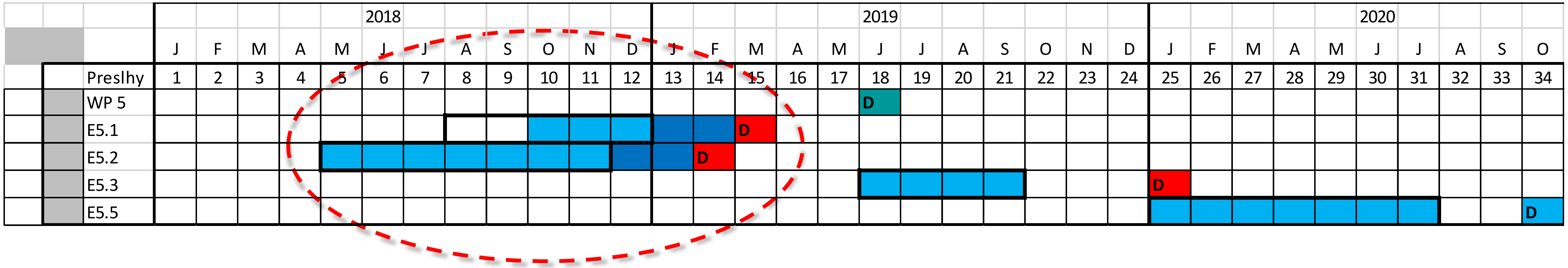
E5.1 Cryogenic hydrogen jet fire experiments with detailed temperature and heat flux measurements (PS, KIT)

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
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E5.1										🟦	🟦	🟦	🟦	🟦	D																			
E5.2					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	D																				
E5.3																		🟦	🟦	🟦	🟦				D									
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Objectives

- To complete the experimental database on cryogenic LH2 combustion, including laminar steady state and turbulent combustion and detonation of LH2 and gaseous hydrogen in air at cryogenic temperatures.
- 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 practical applications. The data obtained can be used for risk assessment and safety distances evaluation for pressure and thermal loads.
- 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
  - LH2 combustion in an enclosure. Effects of pressure, temperature, heat radiation, convection, geometry, pressure peaking
- 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.

Knowledge gaps

- Hydrogen combustion under cryogenic temperatures, at the conditions of very dense real gas state, close to condensed phase density.
- Heterogeneous combustion in presence of condensed (liquid or solid) oxygen, nitrogen, CO_2 and H_2O (above hydrogen spill).
- Effect of cryogenic temperatures on thermodynamics and kinetics of combustion process leading to several times lower speed of sound and viscosity of the gas
- Simultaneous combustion and flush evaporation of hydrogen above the spill of LH_2
- Effect of inverse hydrogen concentration gradient (higher hydrogen concentration at the ground level) on combustion dynamics in a layer geometry (above hydrogen spill).
- Radiation characteristics of LH_2 combustion

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 or numerical results between partners’ simulations
  - Simulations of real accident scenarios relevant to LH2 combustion
  - Generation of simplified engineering correlations for safety analysis
- The phenomena to be considered
  - LH2 jet fire behaviour, including scaling and radiation properties (UU)
  - 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
  - LH2 combustion in an enclosure. Effects of pressure, temperature, heat radiation, convection, geometry, pressure peaking (UU)

Experiments

KIT, PS:

- Cryogenic hydrogen jet fire experiments with detailed temperature and heat flux measurements (E5.1)
- Flame propagation regimes at cryogenic temperatures (E5.2)
- Flame propagation over a spill of LH2 (E5.3)
- BLEVE (E5.4)

HSL:

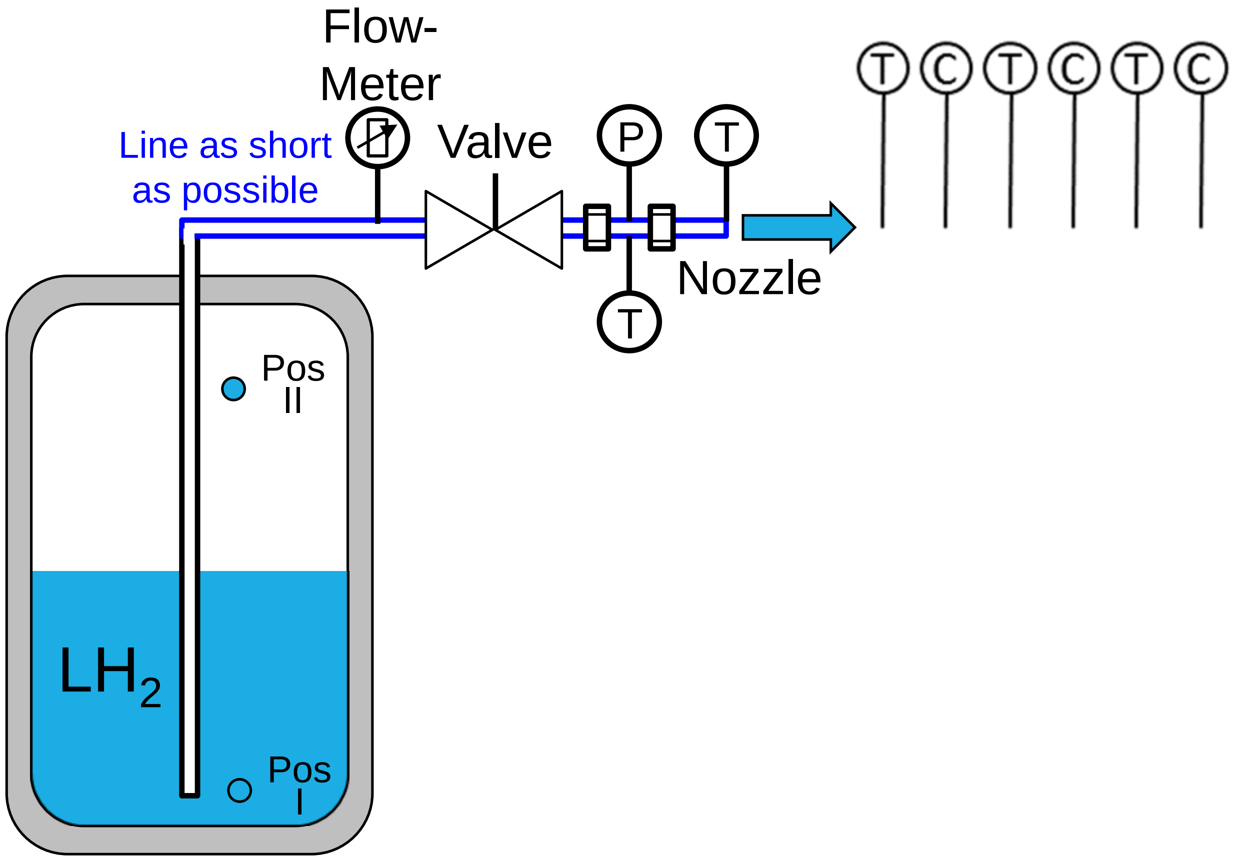
- LH2 Combustion with congestion/confinement variation (E5.5)

Cryogenic hydrogen jet fire experiments

- 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
  - 3 bulk pressures within the range 1-200 bar
  - 3 nozzle diameters (1, 2, 4 mm)
  - 5 ignition locations (0-2 m)
  - 4 time delays (0-1 s)

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 time.



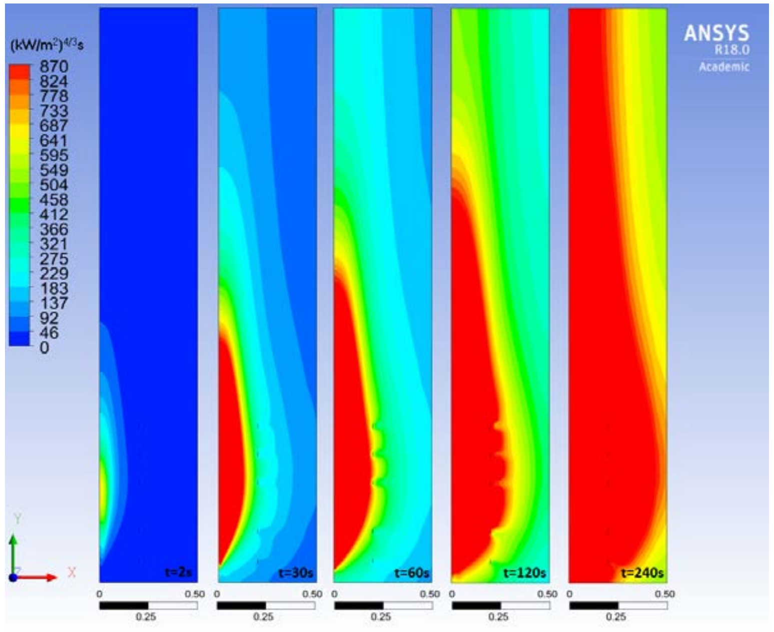
Cryogenic hydrogen jet fires (UU)

Thermal dose calculation

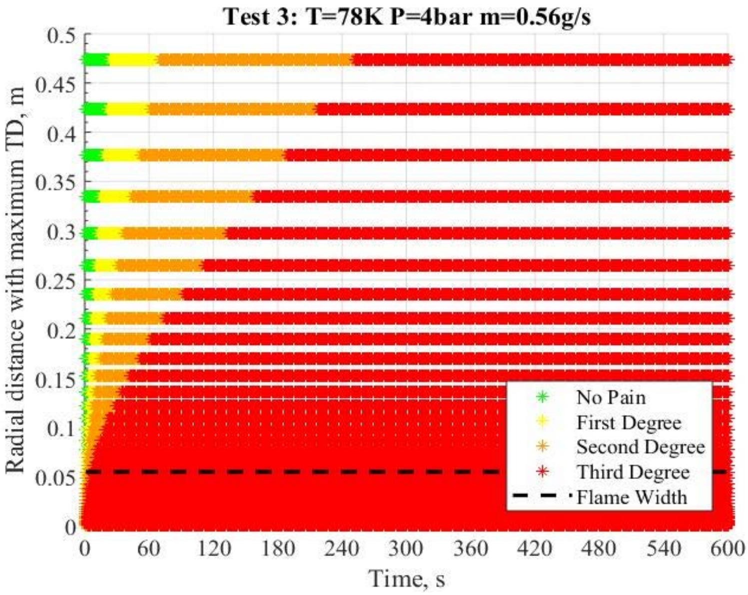
The employed CFD model has been previously validated against experiments by SNL on cryogenic hydrogen fires from storage with pressure up to 5 bar abs and temperature in the range 48-82 K.

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

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



Thermal dose distribution for Test 3



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

TEST MATRIX FOR THERMAL MEASUREMENTS

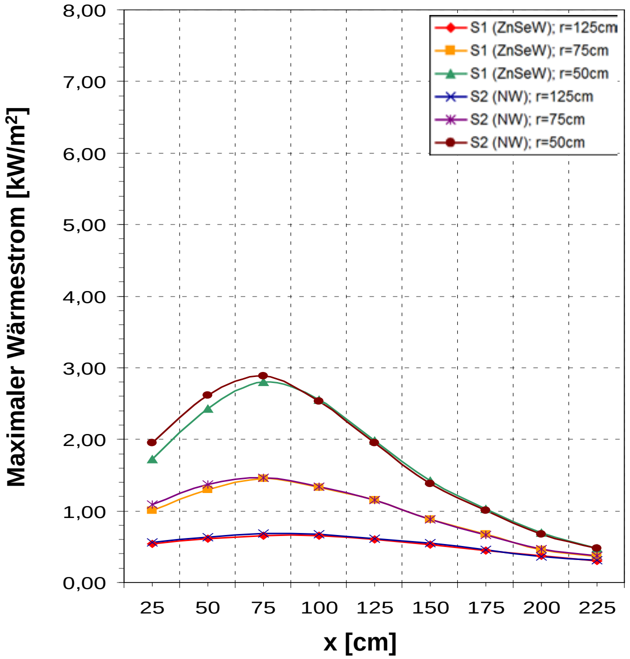
T_0 [K]	t_S [sec]	t_F [sec]	d_0 [mm]	p_0 [bar]	$\dot{m}$ [g/s]
290	**10**	**8**	**2**	**20**	**3,3**
			4	**4**	**3,3**
80	**10**	**8**	**2**	**14**	**3,3**
				20	**4,4**
			4	**3**	**3,3**
				4	**4,4**

t_S:Strahldauer
t_F:Flammendauer

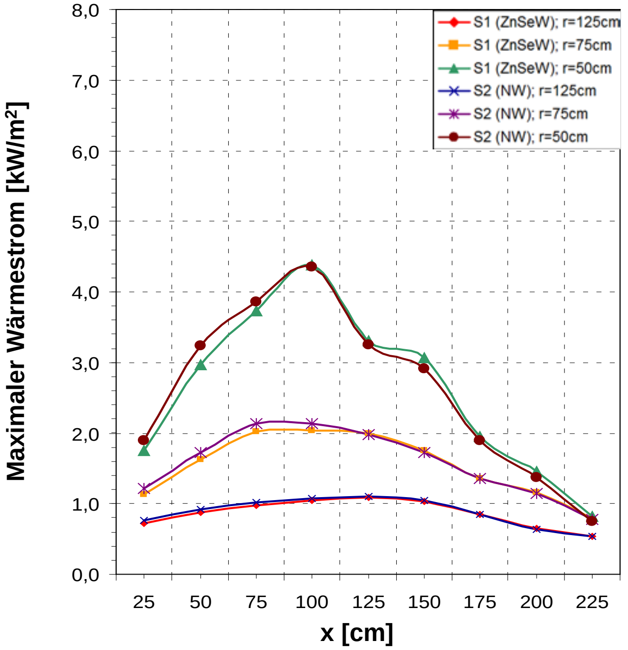
- Zündparameter
  - Zündung: 0,4 m nach Düsenöffnung
  - Zündzeitpunkt: 2 s nach Einströmbeginn
  - Zündzeitlänge: 400 ms

HEAT FLUX MEASUREMENTS IN PARALLEL TO JET AXIS

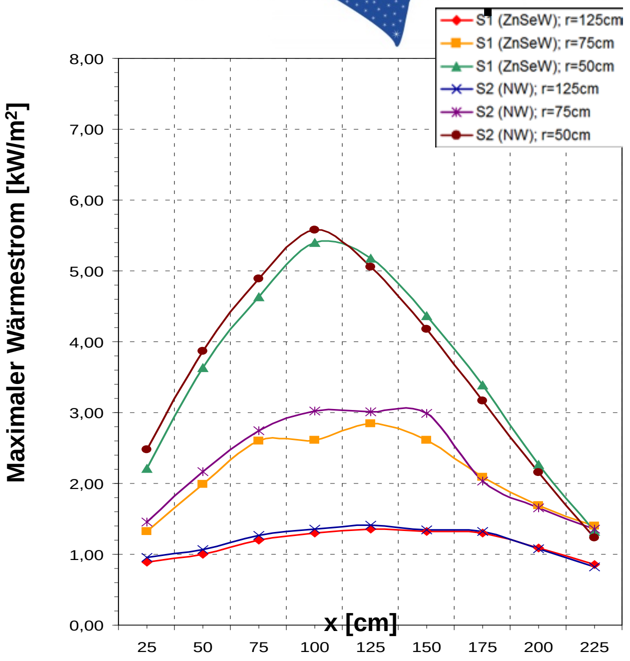
T_0=290K; d_0=2mm, p_0=20bar, $\dot{m}$=3,3g/s



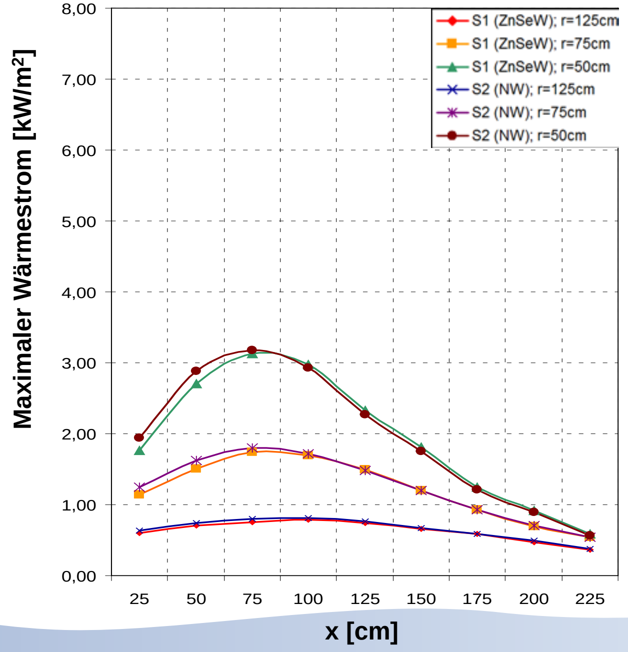
T_0=80K; d_0=2mm; p_0=14bar, $\dot{m}$=3,3g/s



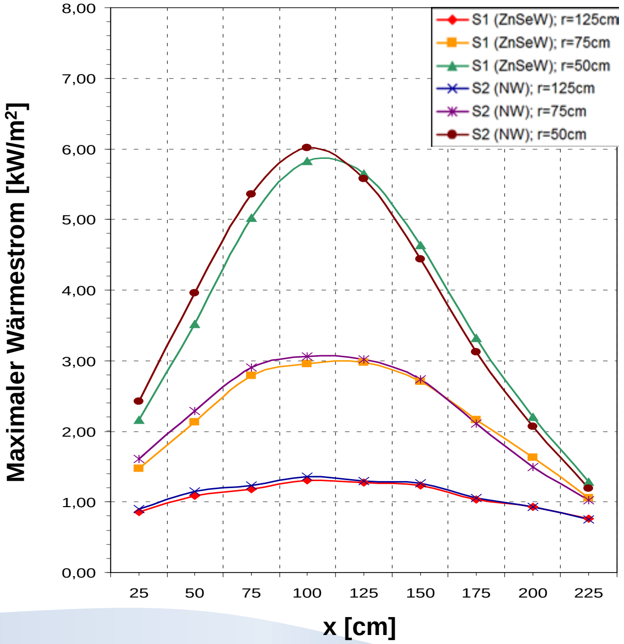
T_0=80K; d_0=2mm; p_0=20bar, m=4,4 g/s



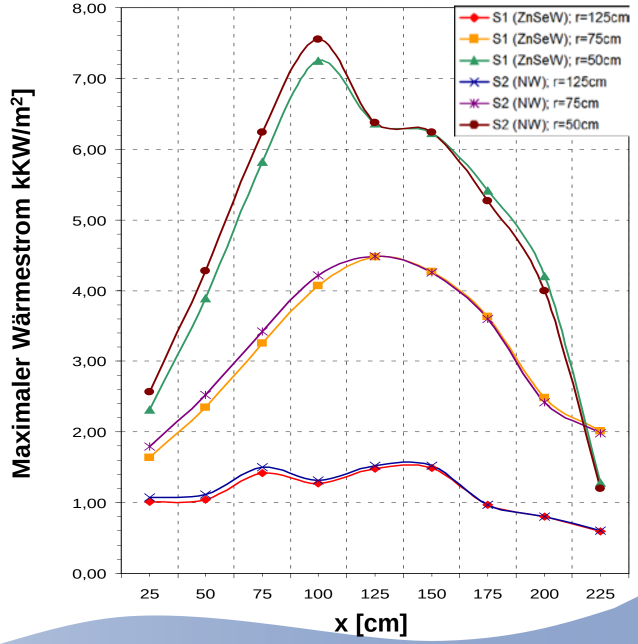
T_0=290K; d_0=4mm, p_0=4bar, $\dot{m}$=3,3g/s



T_0=80K; d_0=4mm; p_0=3bar, $\dot{m}$=3,3g/s



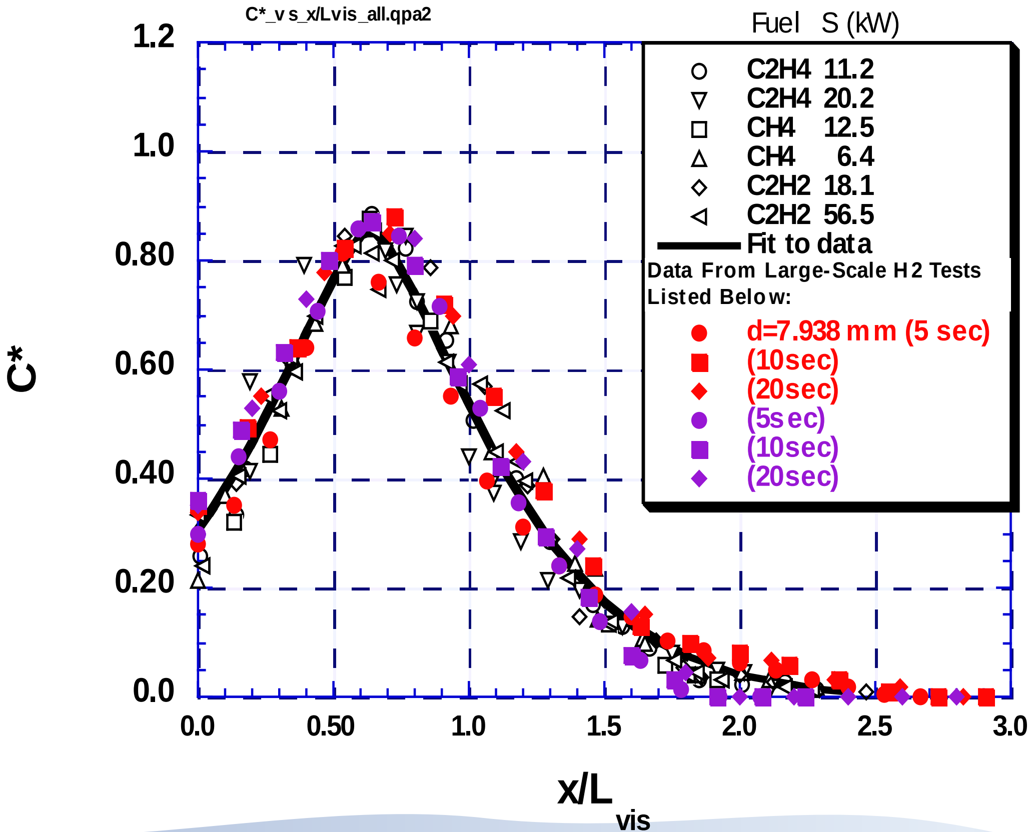
T_0=80K; d_0=4mm; p_0=4bar, $\dot{m}$=4,4 g/s

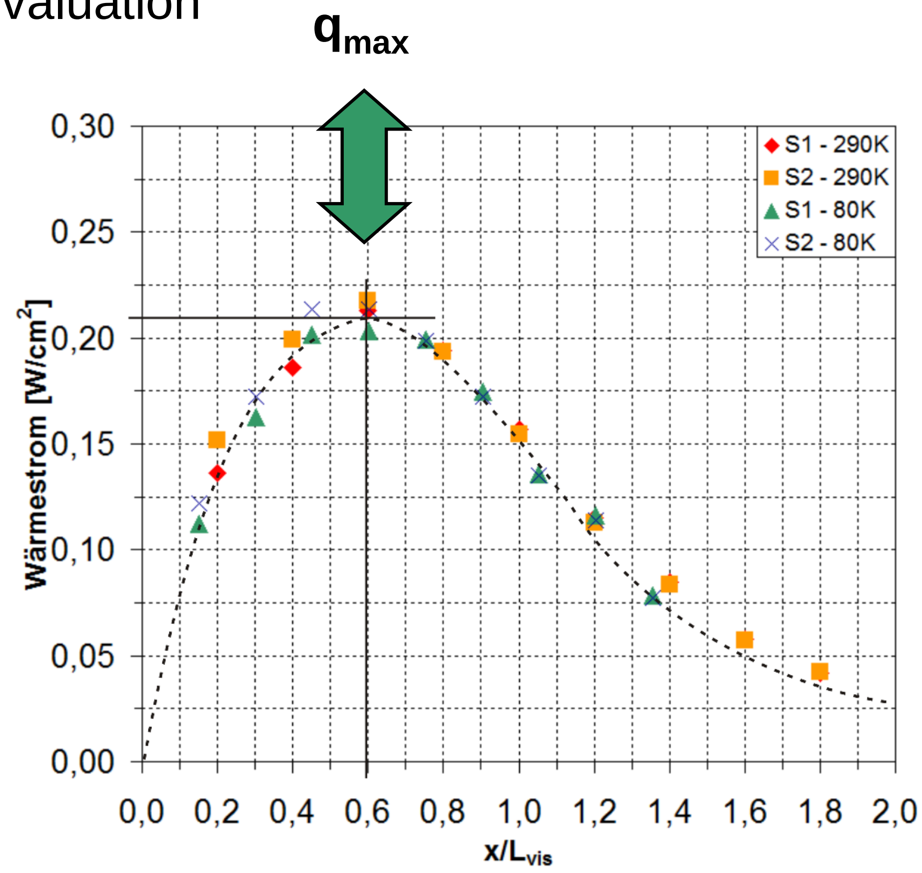


SCALING OF THERMAL MEASUREMENTS

T_0 [K]	d_0	p_0 [bar]	m [g/s]	x_{Qmax} [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





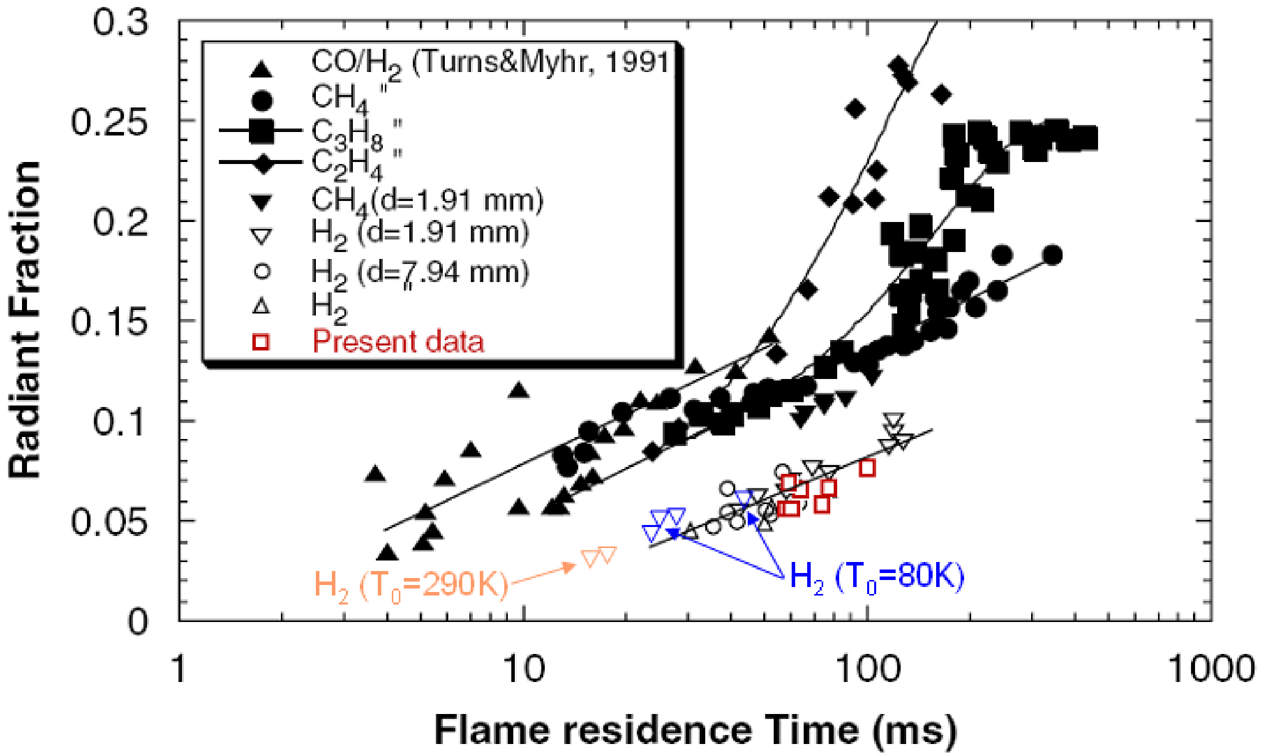
HEAT RADIATION OF HYDROGEN JET

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

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

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

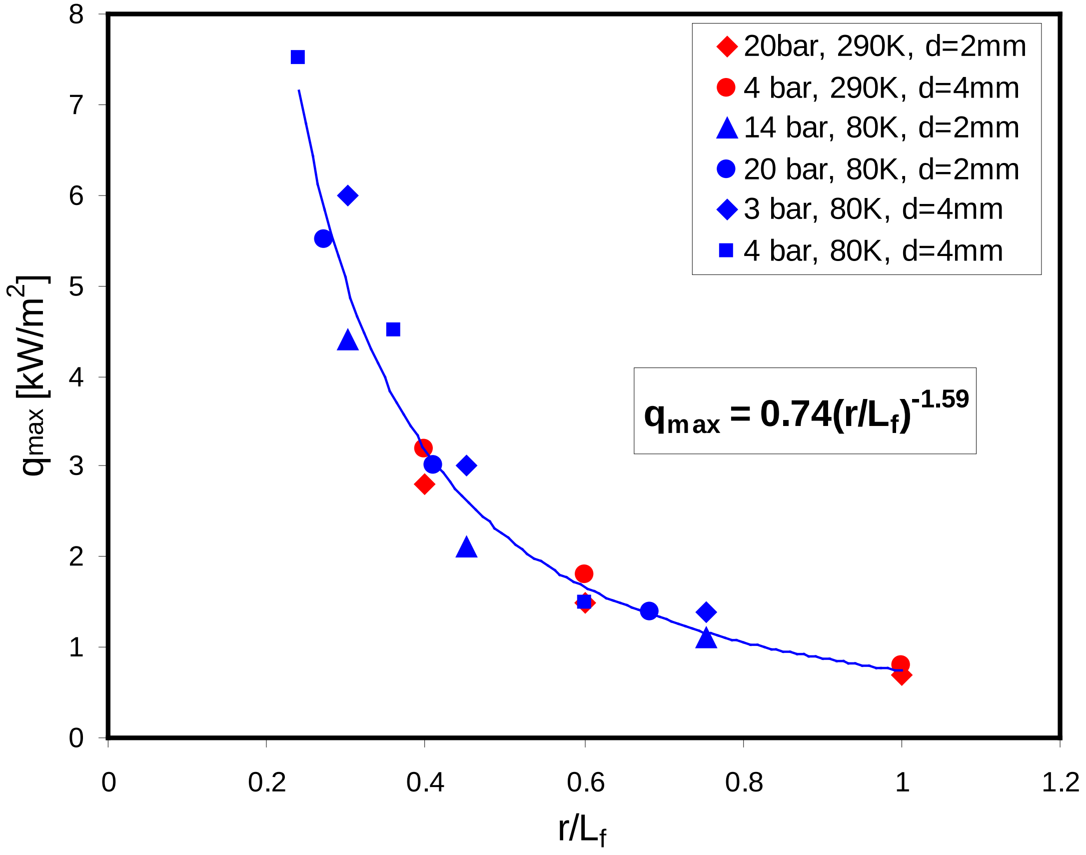


- Typical values of radiant fraction are:
  X_{rad} = 0.03 for 290K
  X_{rad} = 0.06 for 80K
- Radiant fraction depends on jet scale but residence time as a measure of scale is not convenient for practical purposes:

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

- Visible flame length can be used for scaling

SCALING OF THERMAL MEASUREMENTS



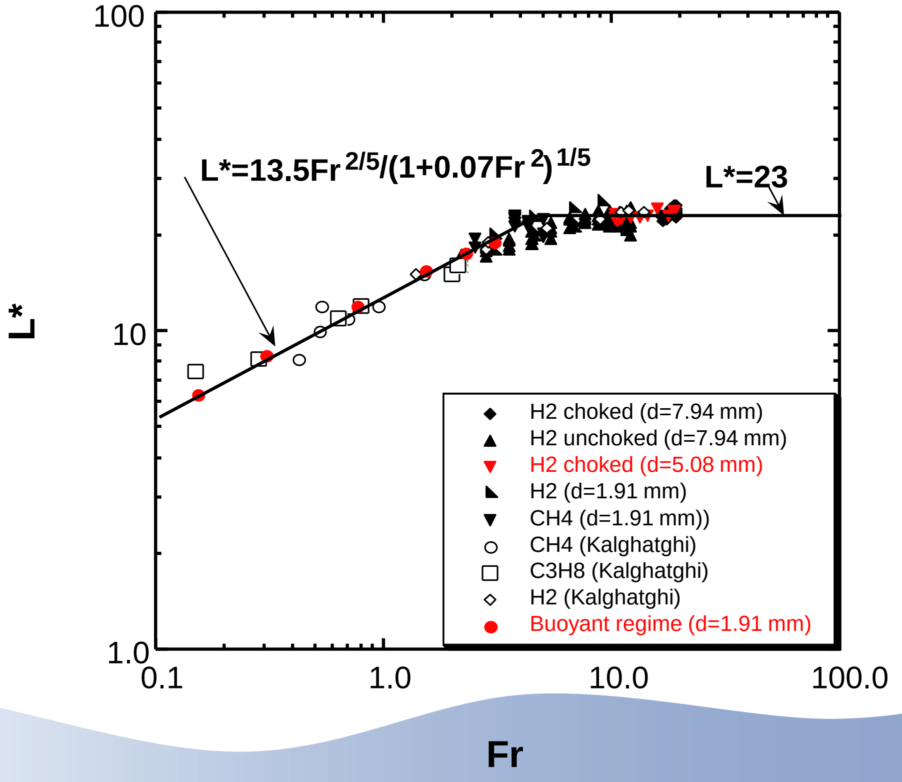
- All experimental data on maximum heat flux for different distances from jet axis **r** normalized by visible flame length $\mathbf{L_f}$ are collapsed in one curve
- For the same mixture and for high momentum jets the visible flame length $\mathbf{L_f}$ is rather simple function of nozzle diameter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

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

- Using scale correlation for maximum heat flux:

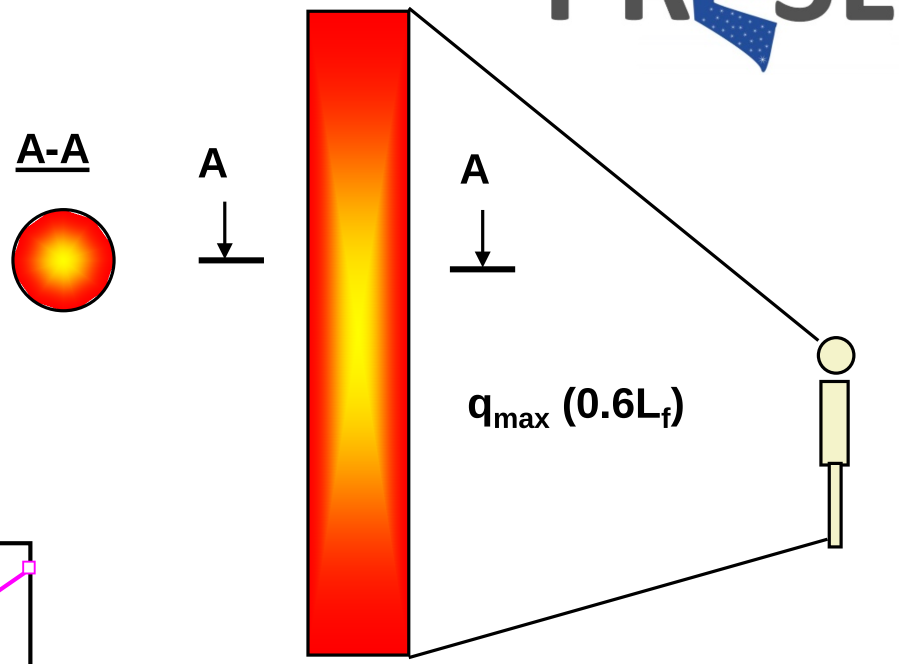
  $$q_{max} = 0.74(r/L_f)^{-1.59}$$

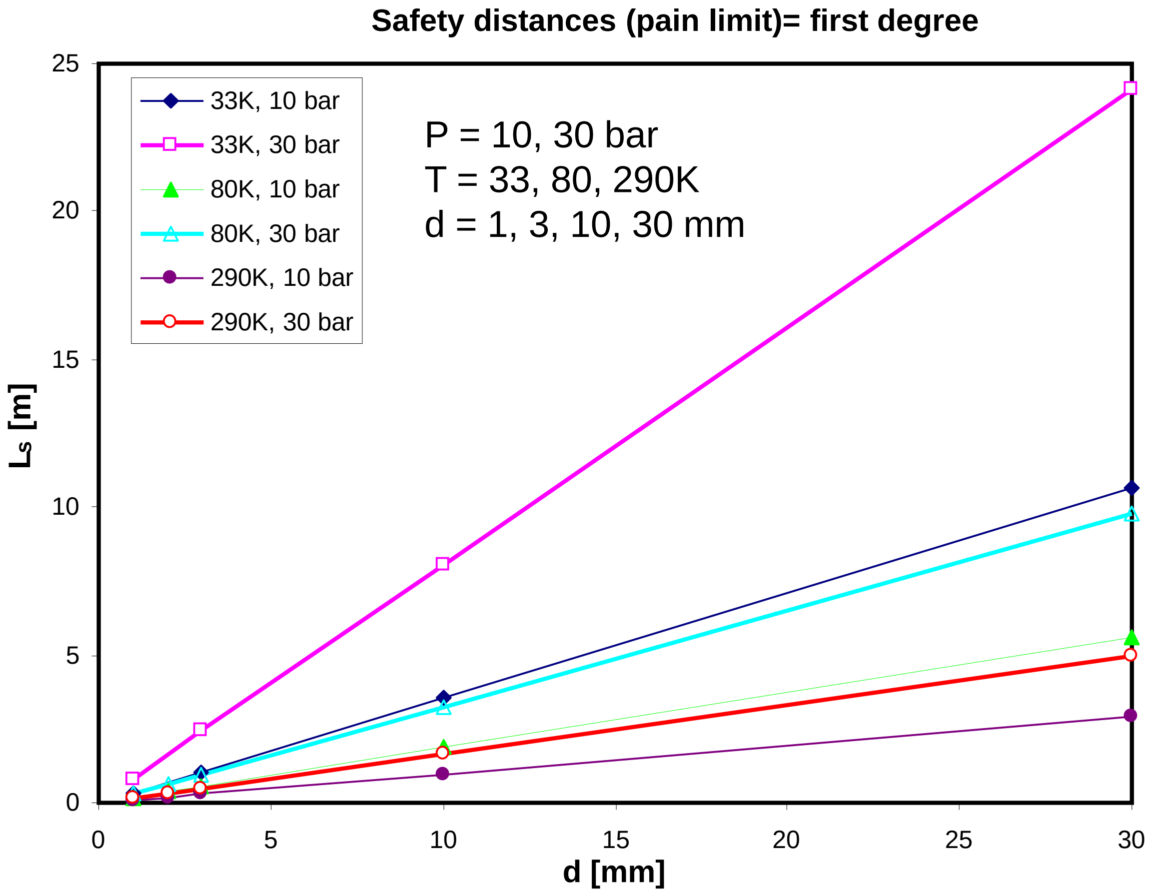
  we can evaluate the safety distance for given level of critical heat flux corresponding, for instance, to pain limit or different burn degree for human skin



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

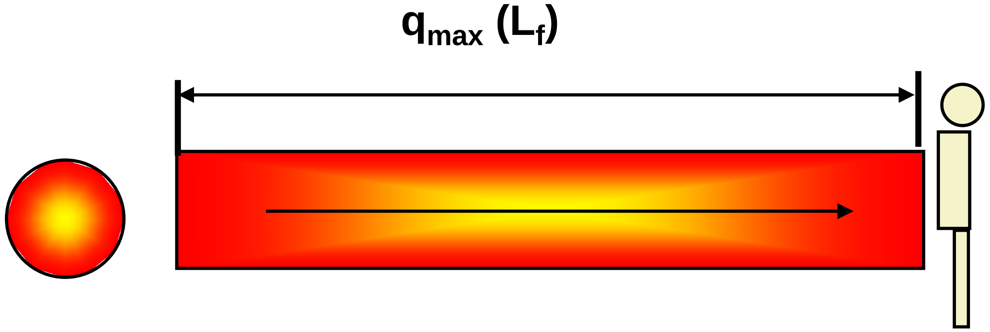


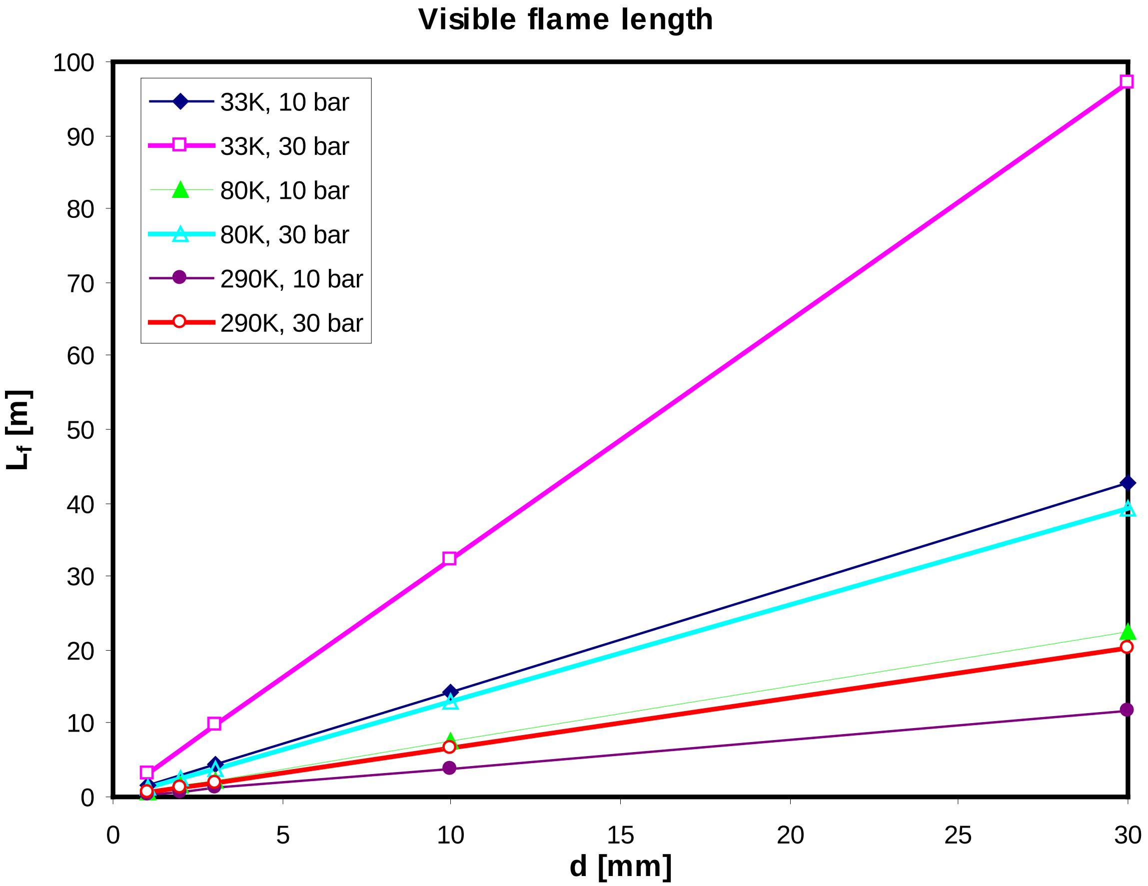


- Safety distances calculated for pain limit at exposure (10 sec)
- Maximum radiation reached at safety distance in the point 0.6**L_f**
- Safety distance increases with nozzle diameter and pressure increase. It decreases with initial temperature increase

SAFETY DISTANCES

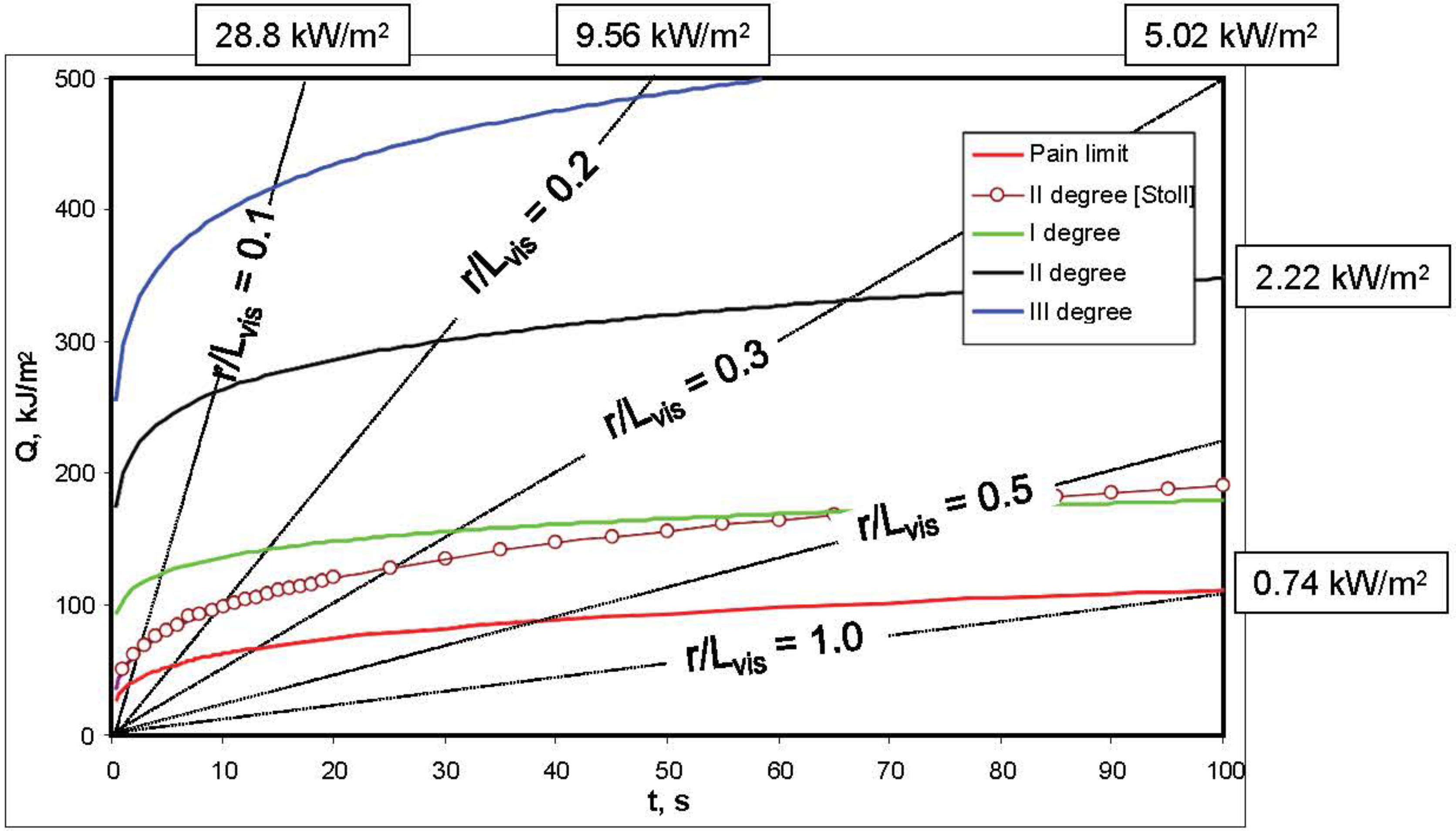
- Side view area **$S = 0.17L_f^2$**
- Axial view area **$S = 0.02L_f^2$**
- As a safety distance for axial position visible flame length can be used **L_f**





- 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

Damage diagram



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

CONCLUSIONS

- Thermal radiation of horizontal quasi-stationary high-momentum hydrogen jets with different nozzle diameters and different mass flow rates in the range from 3.3 to 4.4 g/s at temperatures of 80 and 290 K has been investigated

- Visible flame length was used as a characteristic size of burned hydrogen jet in order to dimensionalyze heat radiation at different initial conditions (pressure, nozzle diameter, temperature)

- Safety distances for pain limit at exposure time 10 sec was calculated for burned hydrogen jet. Safety distance increases with nozzle diameter and pressure increase. It decreases with initial temperature increase.

WP5 - Activities plan and progress (UU)

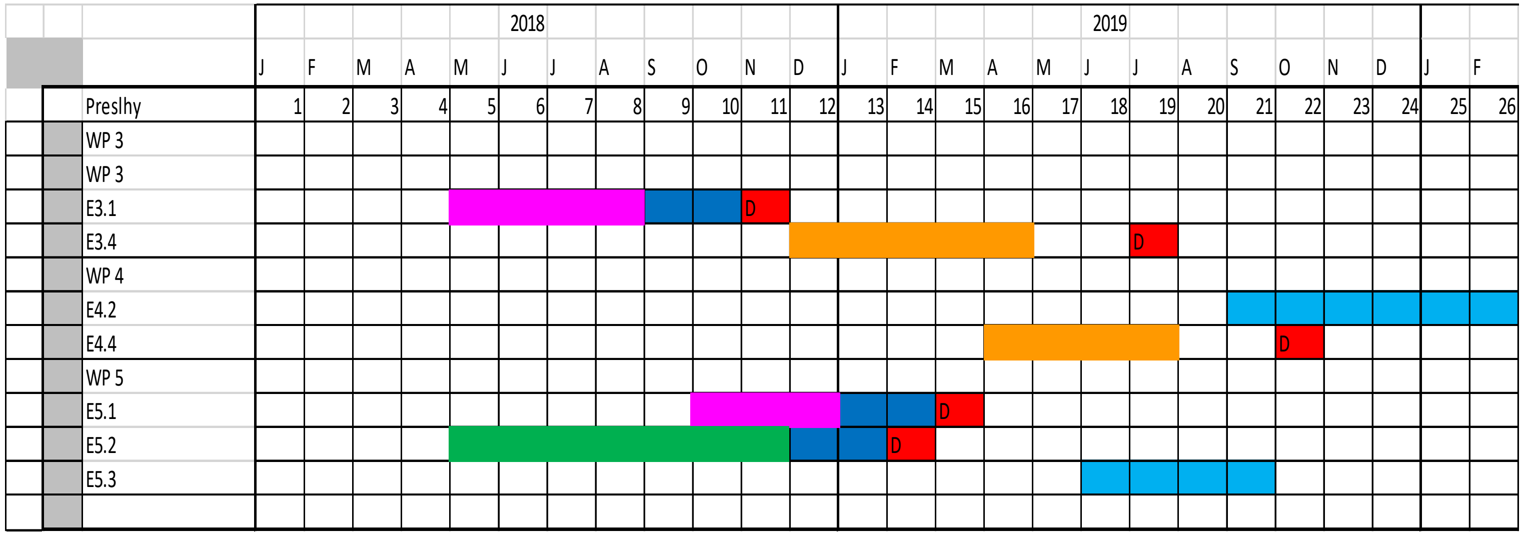
- Development and validation of CFD models and engineering correlations for evaluation of thermal hazards from cryogenic jet fires along and aside the jet axis:
  - ✓ Small scale releases (P up to 6 bar and d=1.25 mm)
  - – Larger scale releases
  - – Hazard distances for horizontal jet fires
  - – Higher pressure releases (P > 10 bar – KIT E5.1)
- Development of UDF for evaluation of thermal dose
- *Simulations on pressure-peaking phenomenon for ignited cryogenic release indoors (if experiment available)*
- *Simulations on BLEVE (if experiments KIT E5.4 available)*

Combustion-Tube-Experiments

- The critical conditions for flame-acceleration and DDT for Hydrogen-Air-Mixtures at cryogenic temperatures will be investigated in WP E5.2,
- The experiments will be performed in the

  Combustion Tube

  that is currently fabricated at the main workshop of KIT



	2018												2019													
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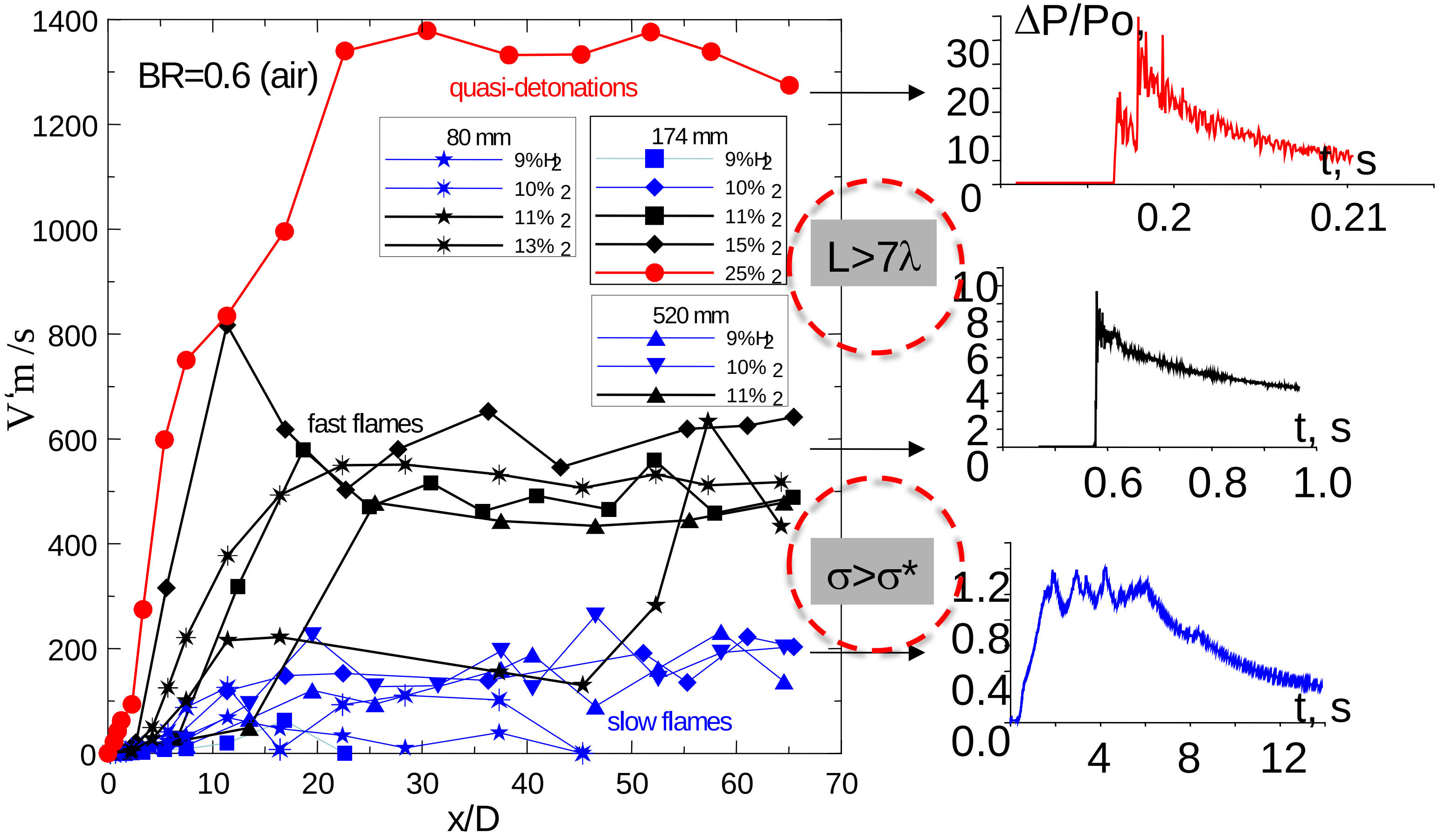
E5.3																		🟦	🟦	🟦	🟦					

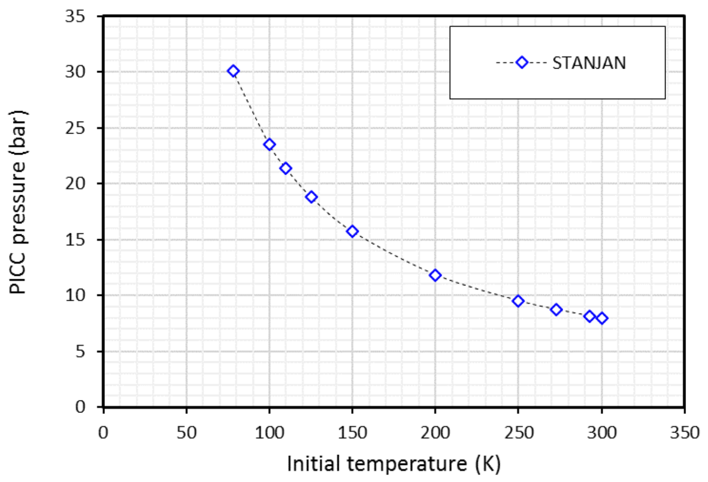
Expected results (reference data)

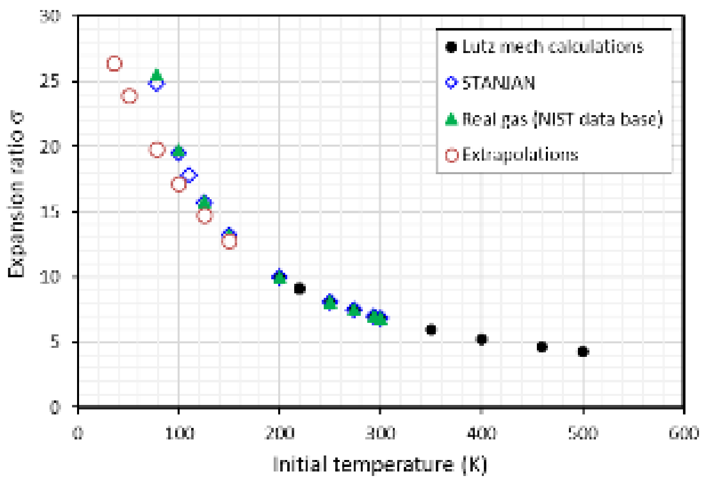
Flame propagation regimes

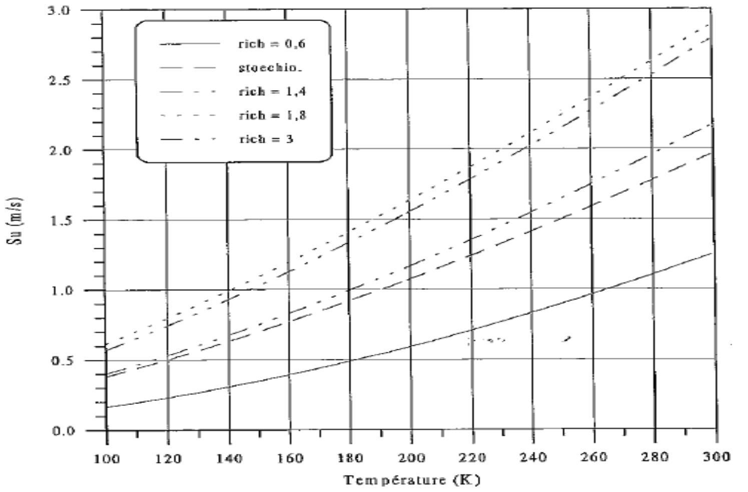


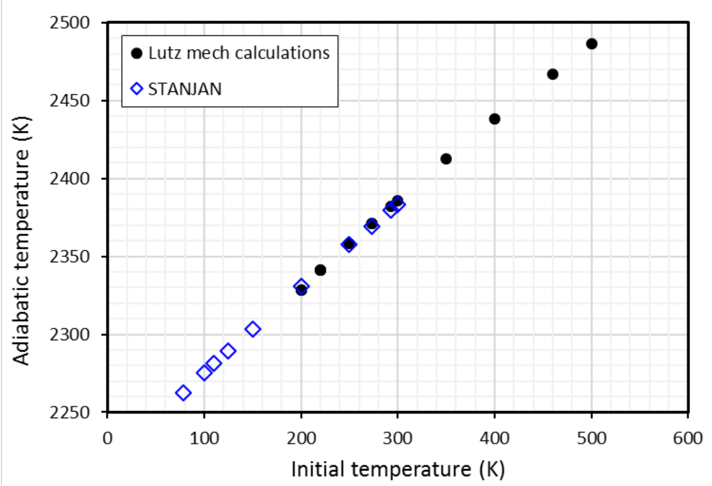
Expected results

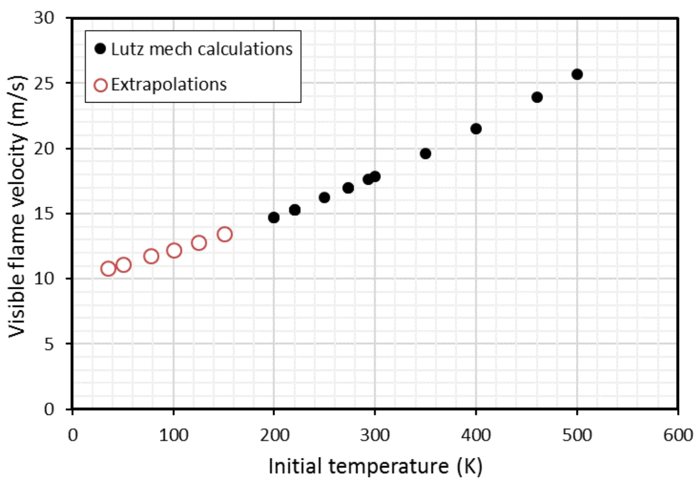
Combustion properties at cryogenic temperatures

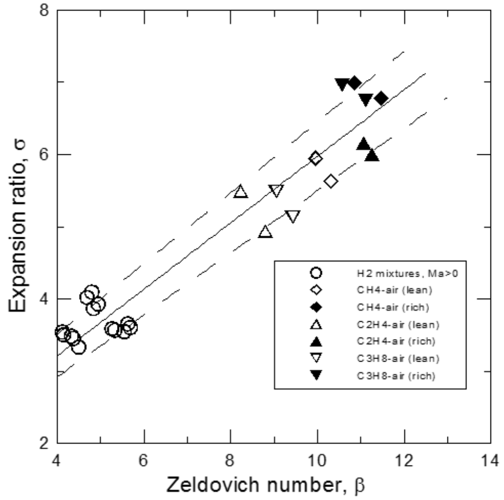








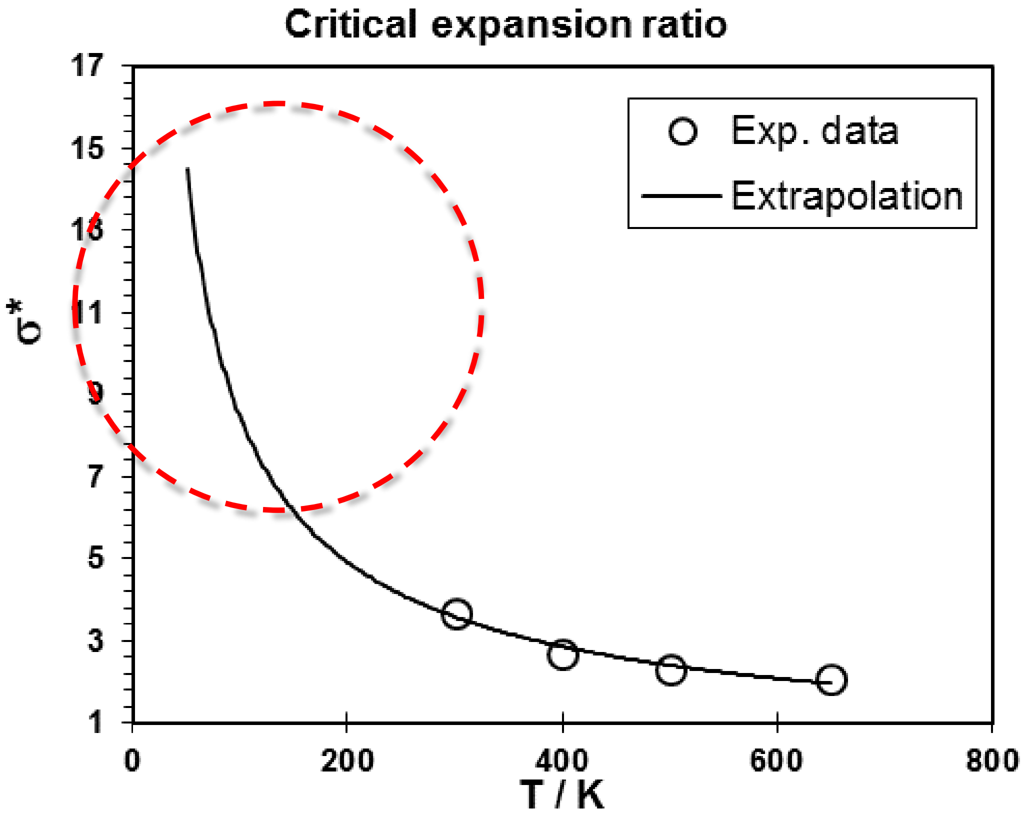




- Lack of fundamental data on combustion properties at cryogenic temperatures
  - ➔ Dramatic changes of expansion ratio, PICC pressure and laminar flame velocity
  - ➔ Not so big changes of TAICC

Prediction of the results

Critical expansion ratio for an effective flame acceleration



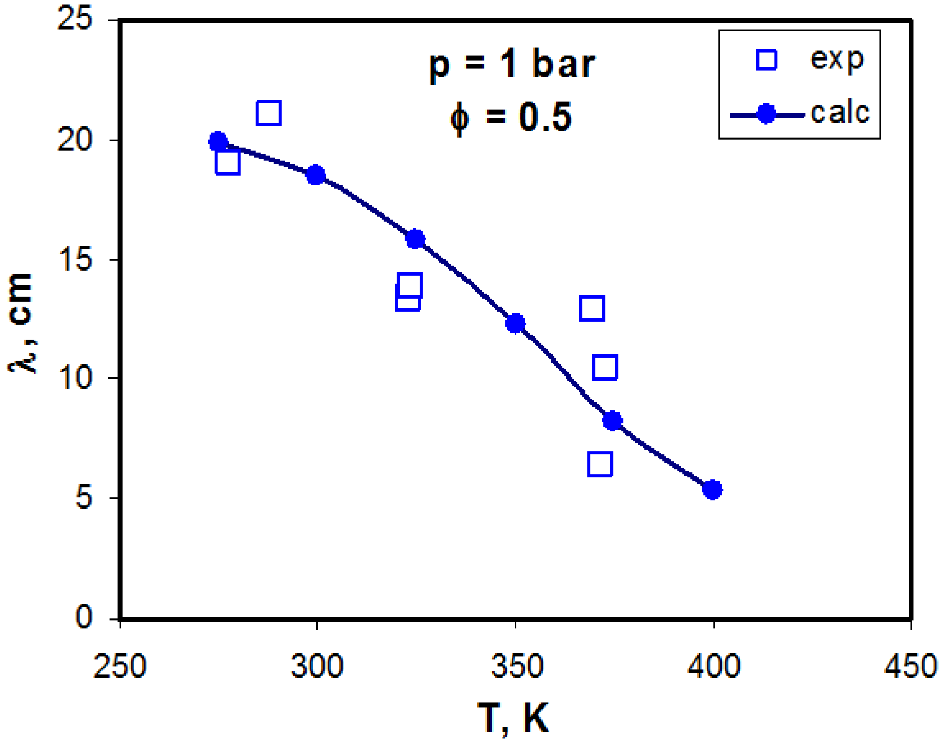
T, K	C_{H2}, %mol	σ*
300	11	3.75
200	10.34	4.92
150	10.09	6.14
100	9.58	8.49
78	9.13	10.67
50	8.60	13.89

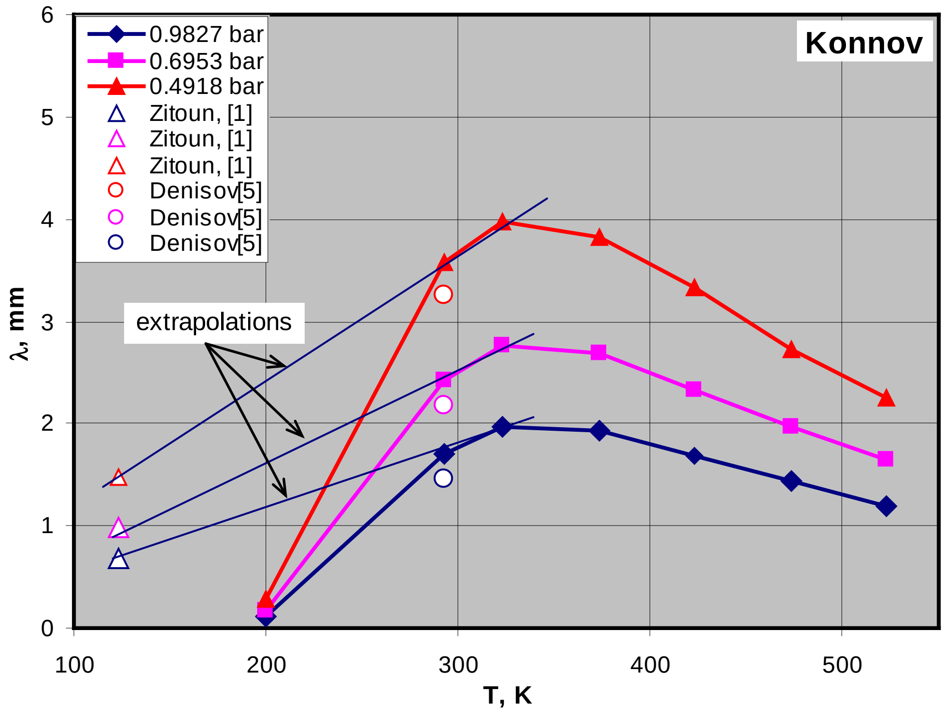
- Lack of fundamental data on combustion properties at cryogenic temperatures
  - ➔ Too far extrapolation to be properly predicted
  - ➔ Cannot be theoretically predicted up to now
  - ➔ Experiments should be done

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
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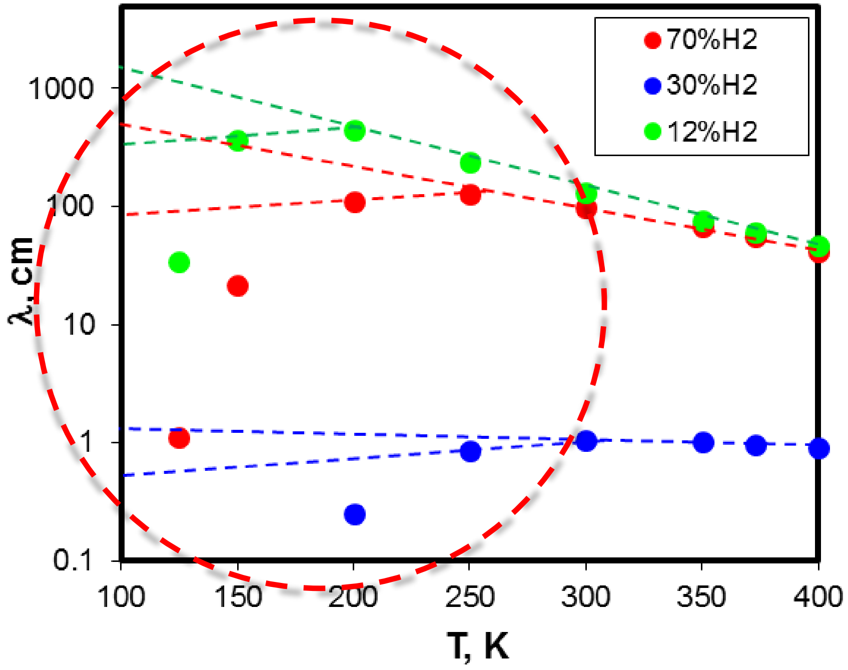
Prediction of the results

Detonation cell size (7λ criterion)



Temperature, T (K)	Detonation cell width λ, cm		
	Hydrogen concentration, %vol.		
	12	30	70
373	61	0.97	55
300	131	1.06	99
250	240	0.85	127
200	450	0.79	112
150	372	0.63	100
100	316	0.50	79

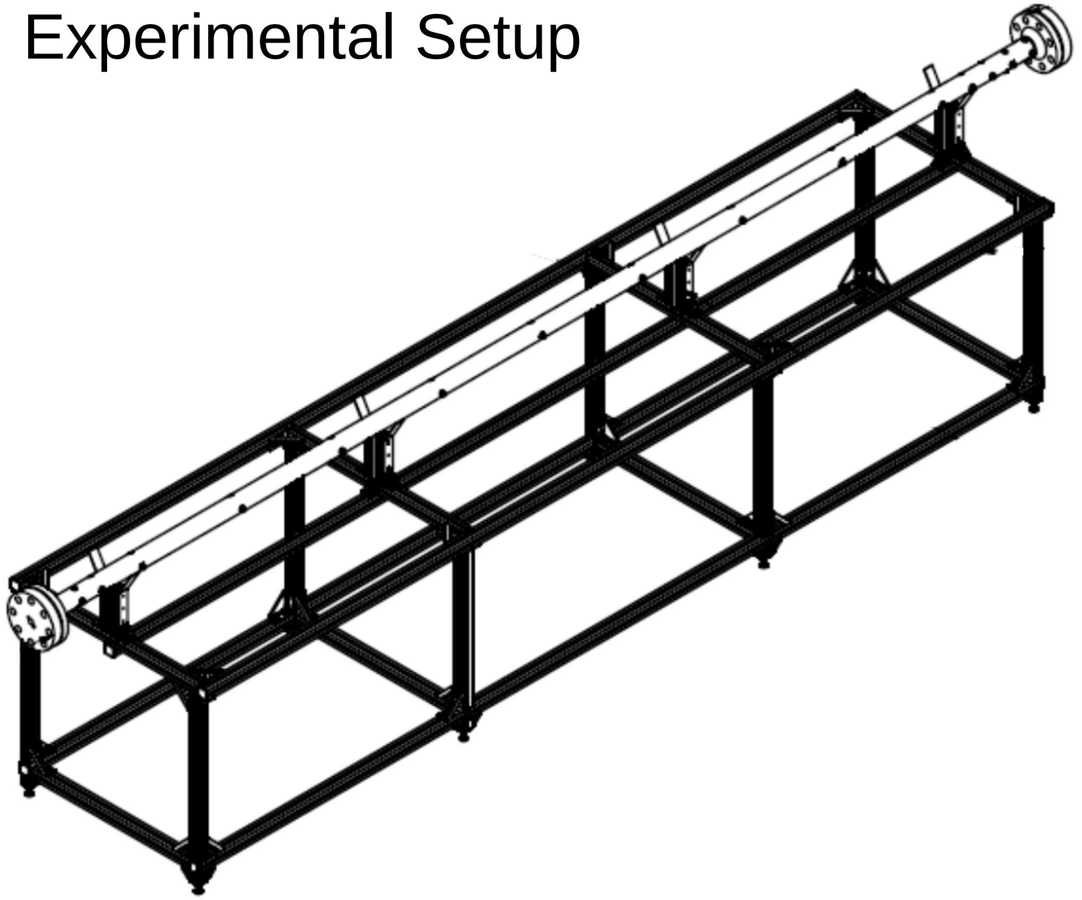
- Lack of fundamental data on combustion properties at cryogenic temperatures
  - ➔ Too far extrapolation to be properly predicted
  - ➔ Could be roughly predicted by numerical tools (CELL_H2)
  - ➔ Experiments should be done (sooted plates technique)

Flame propagation over a spill of LH2

- 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%)

E5.2: Combustion-Tube-Facility

- 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.

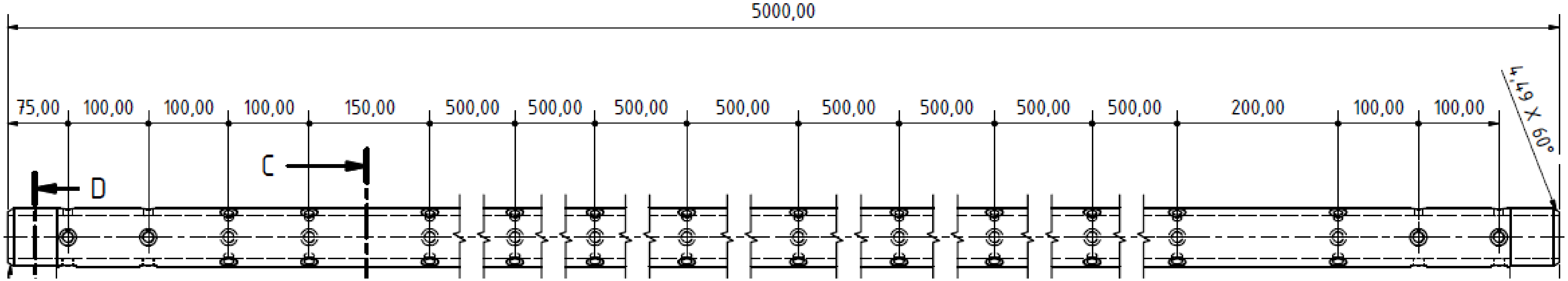
E5.2: Combustion-Tube-Facility

- Current Status

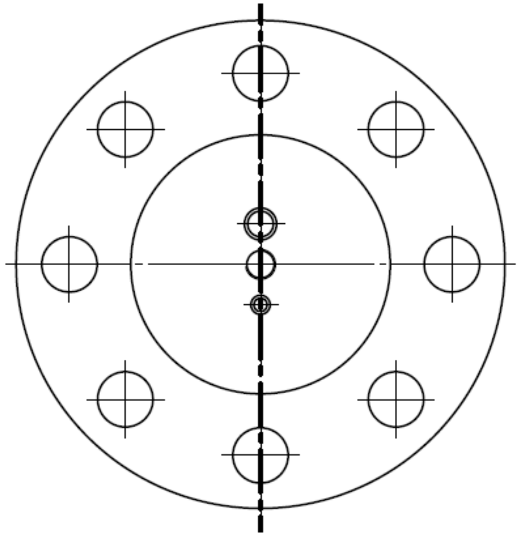
- Tube and flanges currently in KIT-workshop for welding, assembly and installation of ports,
- Dimensions:
  L = 5000 mm
  D_{in} = 54 mm
  D_{out} = 73 mm.

E5.2: Combustion-Tube-Facility

- Shock-Tube

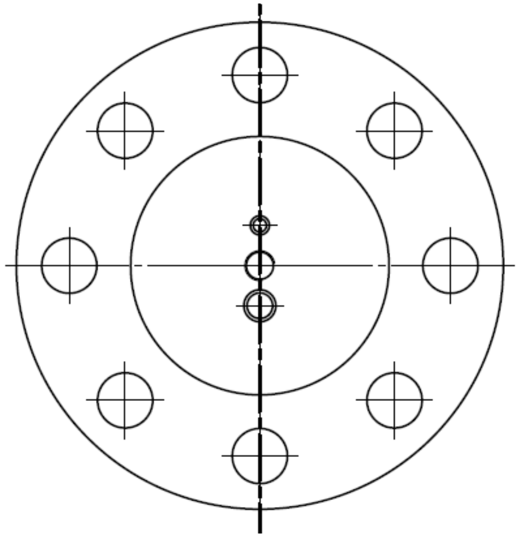


- Front-Flange with ports for:



  - Gas-Inlet
  - Glow-Plug
  - Thermocouple

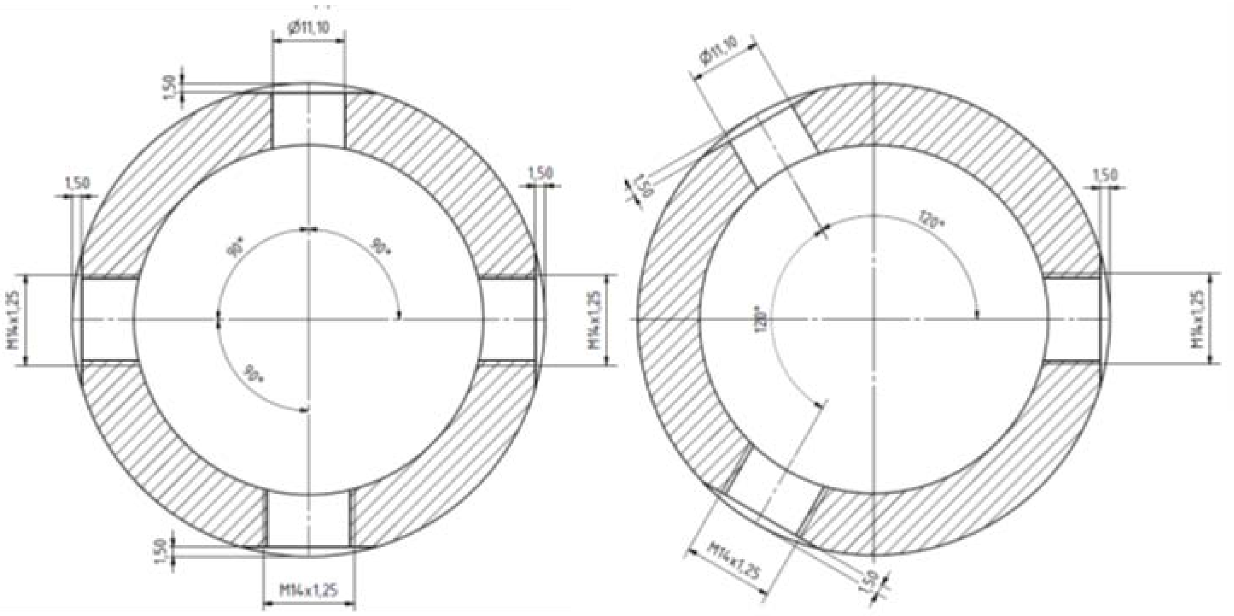
- End-Flange with ports for:
  - Thermocouple
  - Pressure-Sensor
  - Gas-Outlet



- Along the tube 52 ports for:
  - Pressure Sensors (2 different types),
  - Phototransistors

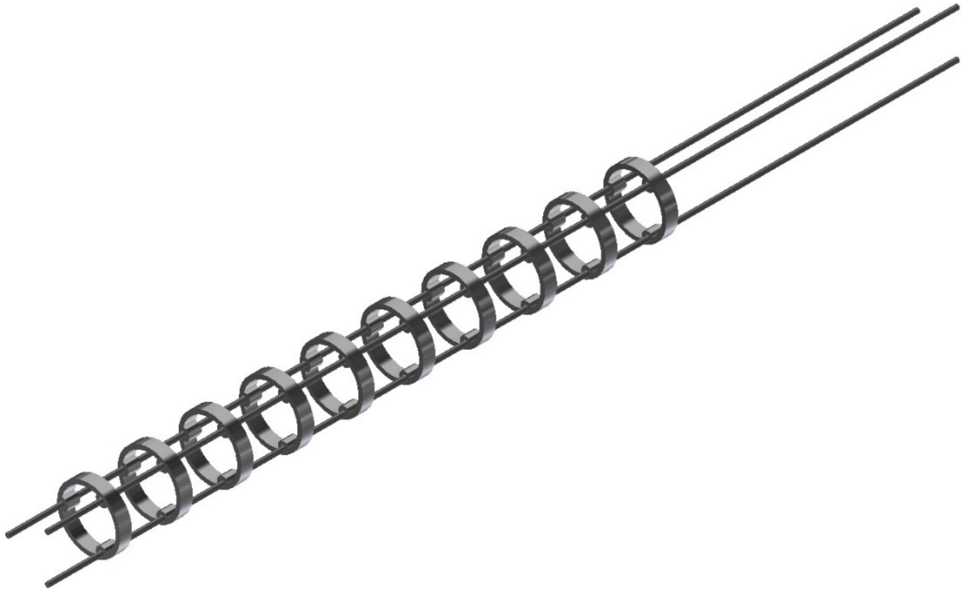
E5.2: Combustion-Tube-Facility

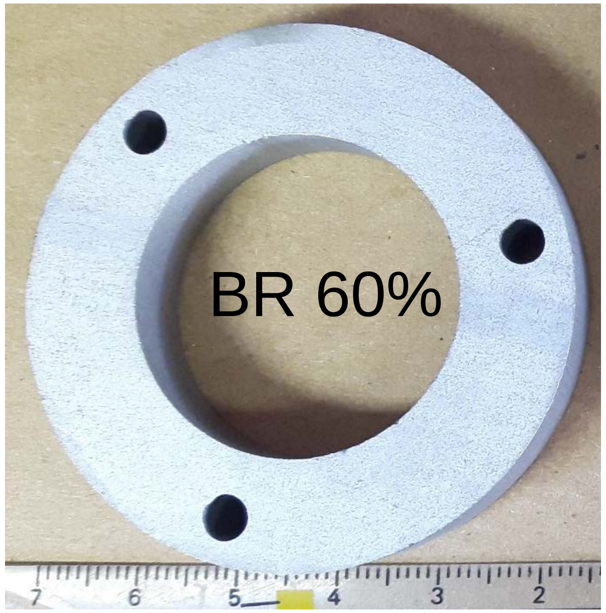
- Instrumentation
  - Ports arranged in groups of: 4 ports (close to ends) and 3 ports (main part of tube) evenly distributed along the circumference.
  - Ports for Phototransistors and small Pressure Sensors for higher pressures (700 bar) are the same,
  - Ports for larger Pressure Sensors (lower pressures, 7 bar) are significantly larger.
  - For fabrication reasons (deformation of tube due to welding of different adapters) the large ports will be distributed helically in the positions along the tube.



E5.2: Combustion-Tube-Facility

- Obstacles





  - 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

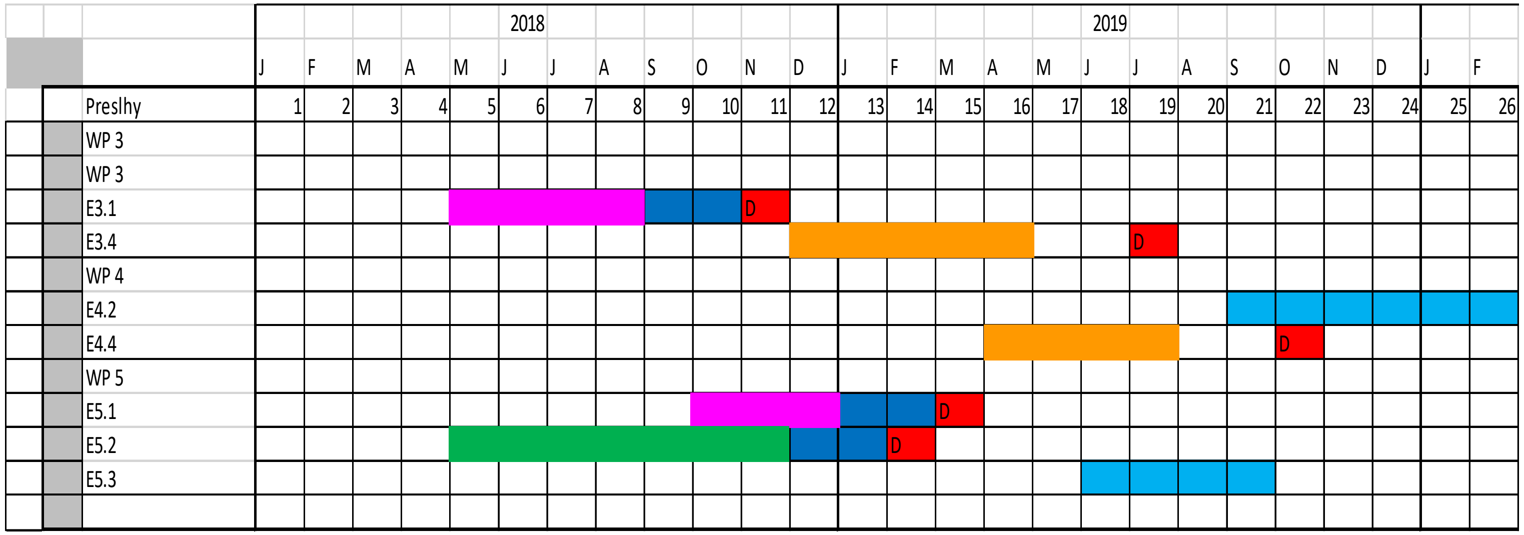
- Planned Procedure
  - Tube is evacuated and purged with gaseous nitrogen several times,
  - Tube is carefully filled with LN2 until a liquid phase stays inside,
  - Tube is kept in this state for several minutes to achieve thorough cooling of the complete tube to approx. 80 K,
  - Tube is drained through a sensor port close to the end flange,
  - Tube is again evacuated several minutes to remove the remaining nitrogen,
  - Evacuated tube is filled with test mixture generated by mass flow controllers (bypass flow during initial phase of mixture generation),
  - All valves to the tube are closed,
  - If a higher temperature than 80 K is desired the tube is left to warm up for some time,
  - Mixture is ignited by a glow-plug.

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)

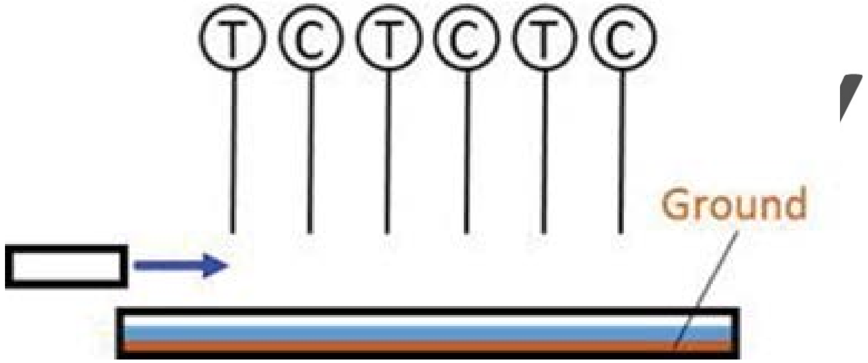
POOL-Experiments

- In the Description of Work 7 two experimental series’ are listed that will be performed by Pro-Science in the **Pool-facility** at KIT-HYKA
  - E3.4: Pool-experiments (unignited) and
  - E4.4: DISCHA-experiments (ignited)



	2018												2019													
	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
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
WP 3																										
WP 3																										
E3.1					🟪	🟪	🟪	🟪	🟦	🟦	D															
E3.4												🟧	🟧	🟧	🟧	🟧			D							
WP 4																										
E4.2																					🟦	🟦	🟦	🟦	🟦	🟦
E4.4																🟧	🟧	🟧	🟧			D				
WP 5																										
E5.1										🟪	🟪	🟪	🟦	🟦	D											
E5.2					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	D												
E5.3																		🟦	🟦	🟦	🟦					

Pool-Facility

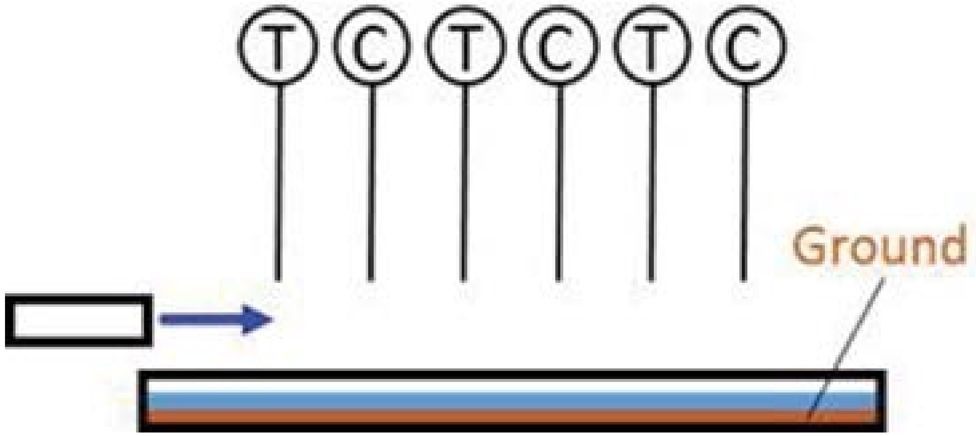


- Experiments according to Proposal
  - Main objective: investigate evaporation rate from an LH2 pool and the cold gas mixing phenomena in the near field above the pool (➔ validation of pool models and CFD dispersion models).
  - Currently it is planned to carry out the tests in a closed facility (e.g. H110 inertized with N2) or free field, with a horizontal frame or an insulated base plate with an area of approx. 1 m^2 for the LH2 pool.
  - Measurements include: ~~Evaporation rate~~, temperature profile (heat flow) in soil, BOS imaging (Fog!!!), temperature profile in gas, concentration profile in gas (hydrogen, oxygen and humidity with sampling probes), ~~velocity profile in gas~~ and atmospheric environment conditions (temperature, pressure, humidity).
  - Measurements allow investigation of oxygen, nitrogen, moisture deposition within the pool and the potential for oxygen enrichment in the gas.
  - Parameters to be examined are:
    3 ground materials (solid, liquid(?), porous),
    3 initial temperatures in the range (77-300 K)
    A special ventilation system simulates different transverse wind conditions.

Color Code
possible
difficult
very difficult/~~impossible~~

Pool-Facility

- Possible Experiments



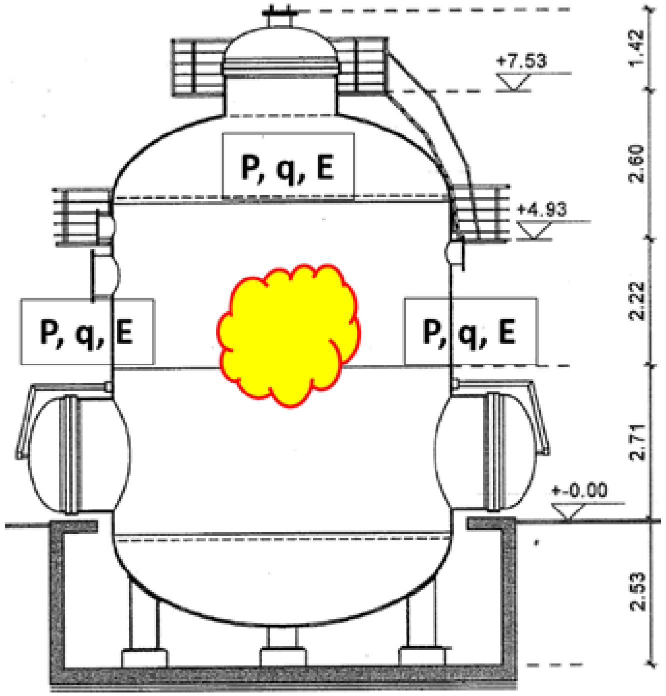
  - It seems to be difficult to generate a pool of LH2 with a surface of 1 m² with a reasonable budget for the enormous amount of LH2 that has to be spilled.
  - If the pool is generated the atmosphere around it will consist of gaseous H2 with traces of other gases

➔ Desired conditions and parameter settings have to be fixed clearly to allow reliable planning of the facility!

To be defined (facility cannot be moved once it is installed):
Height of basin
ground materials

Experimental facility

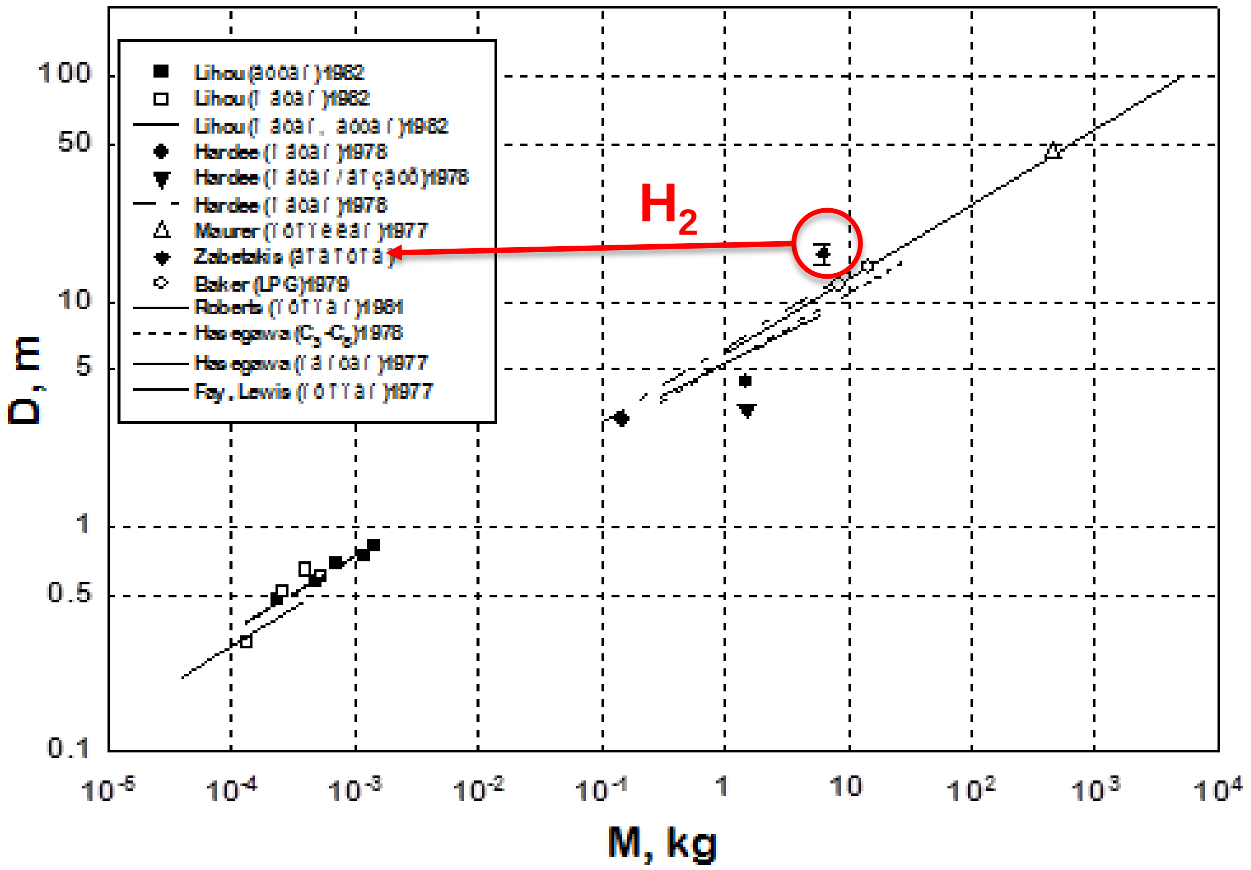
HYKA A2 (V = 220 m^3)



- 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

Expected results

Maximum radius of fireball



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

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

$$E = 8.085 \cdot M_f.$$

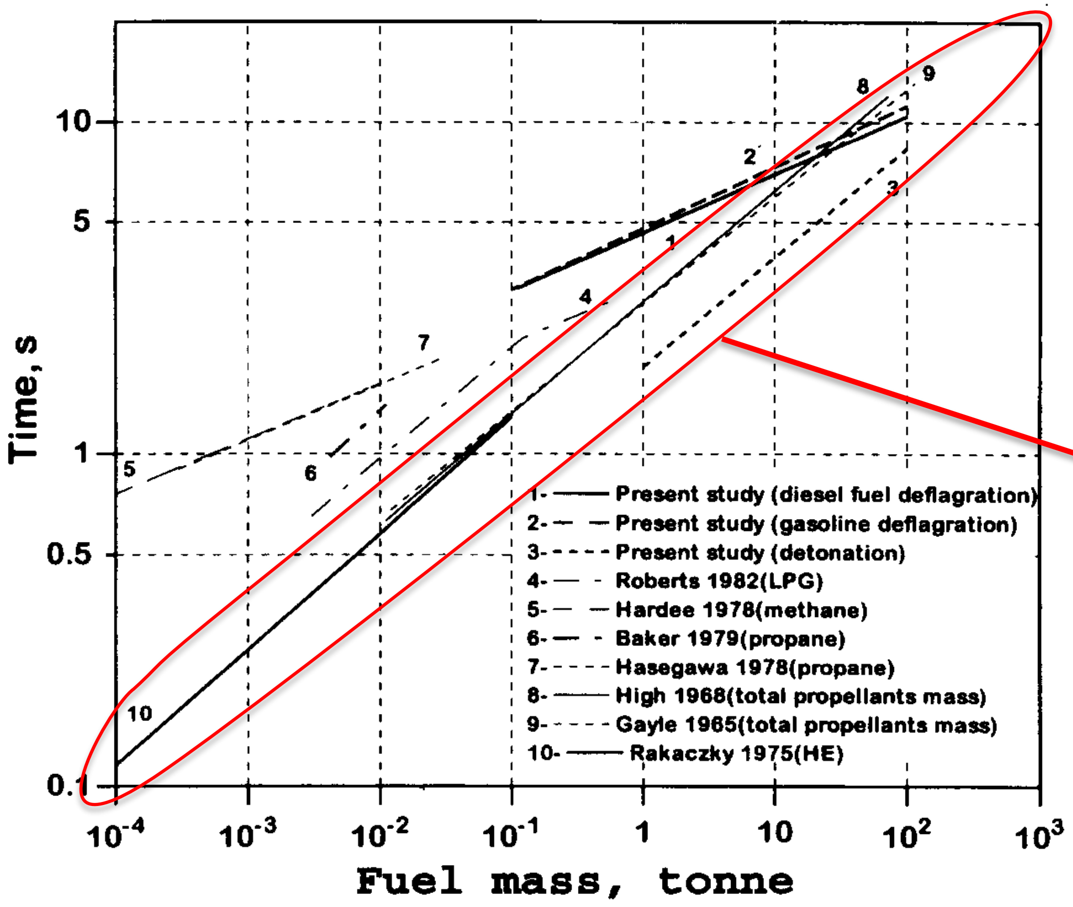
- Lack of fundamental data on hydrogen fireball characteristics at cryogenic temperatures

→ 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