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SAFETY CONSIDERATIONS FOR HYDROGEN TEST CELLS

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3rd International Conference on Hydrogen Safety
Ajaccio/France

September 16 – 18, 2009

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Objectives

- Identify fuel properties of hydrogen that are relevant to safety, test cell design and layout
- Classify safety equipment that is unique to hydrogen as a fuel
- Analyze sample hydrogen test cell setups in respect to
  - Test cell ventilation
  - Hydrogen storage and distribution infrastructure
  - Safety system

Comparison of fuel properties

Parameter	Symbol	Unit	Gasoline	Methane	H_2
Density	ρ	kg/m^3	730-780[I]	0.72[I]	0.089[I] 71[II,III]
Stoichiometric air demand	L_{St}	kg_{air}/kg_{fuel}	14.7	17.2	34.3
Lower heating value	H_u	MJ/kg_{Kst}	43.5	50	120
Mixture calorific value[V]	$\bar{H}_G$ H_G	MJ/m^3	3.82 3.82	3.4 3.76	3.2 4.53
Boiling temperature[III]	$T_{Boiling}$	°C	25-215	-162	-253
Ignition limits[IV]		Vol-% λ	1.0-7.6 0.4-1.4	5.3-15 0.7-2.1	4-76 0.2-10
Minimum ignition energy[III,IV,V]	$E_{Ignition}$	mJ	0.24	0.29	0.02
Self-ignition temperature	$T_{Ignition}$	°C	approx. 350	595	585
Diffusion coefficient[I,IV]	D	m^2/s	-	1.9×10^{-6}	8.5×10^{-6}
Quenching distance[III,IV,VI]		mm	2	2.03	0.64
Laminar flame speed[IV,V]	v_{lam}	cm/s	40-80	40	200
Carbon content	C	Mass-%	86	75	0

[I] at 1.013 bar und 0 °C [II] at –253°C [III] at 1.013 bar [IV] in air [V] λ=1 [VI] at 20°C

Ventilation system design

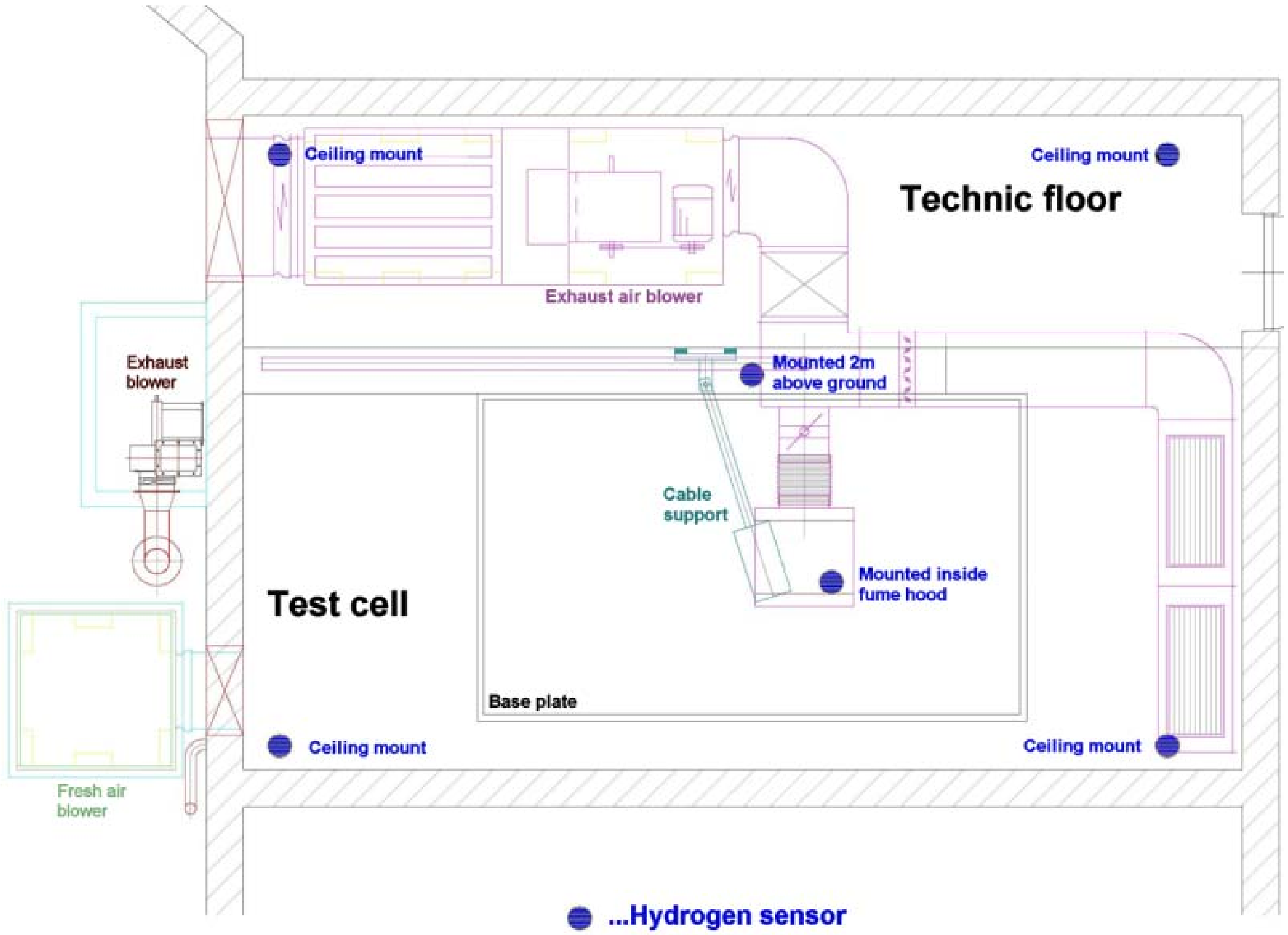
Ventilation flow requirements

Ignition sources can't be excluded – avoid build-up

Hydrogen safety equipment

- **Ventilation**
- **Hydrogen sensors**
  - Various types
  - Commonly used concentration for alarm activation is around 1 Vol-%
- **Hydrogen flame cameras**
  - Thermal fire detectors (need to be located at or very near the site of a fire)
  - Optical sensors (two spectral regions: ultraviolet (UV) and infrared (IR)).
  - Imaging systems
    - Thermal IR
    - UV imaging systems
    - A broom
- **Safety related instrumentation**
  - Exhaust analyzer
  - Fuel flow meter
- **Integrated emergency system**

Sample test cell ventilation systems (closed cell)

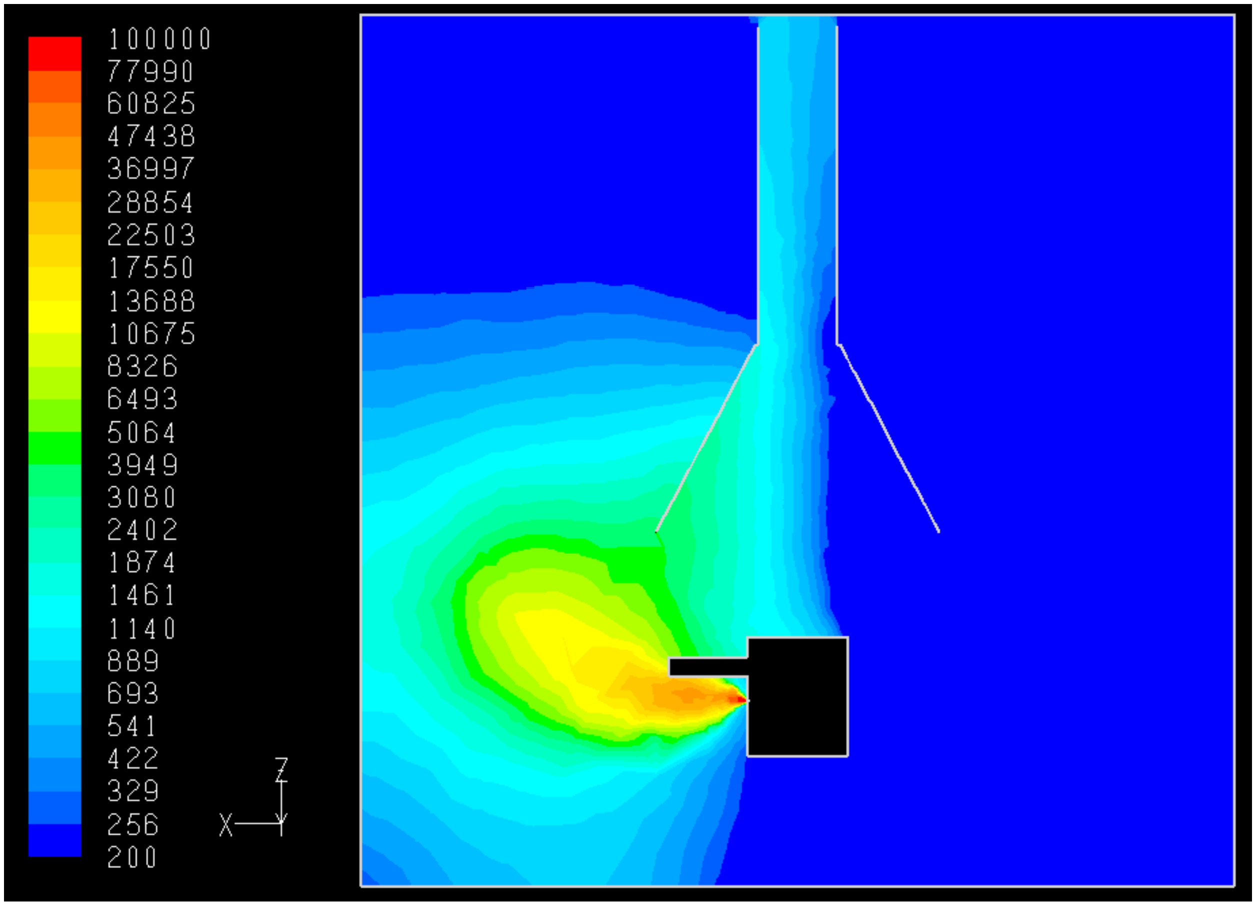


- **Ventilation**
  - Cross ventilation
  - Fresh air supply close to test cell floor
  - Exhaust air close to ceiling
  - Fume hood atop engine
  - Additional exhaust pipe from highest point
- **Several hydrogen sensors throughout test cell**
  - Ceiling
  - Hydrogen distribution
  - Inside fume hood

Sample test cell ventilation systems (open cell)

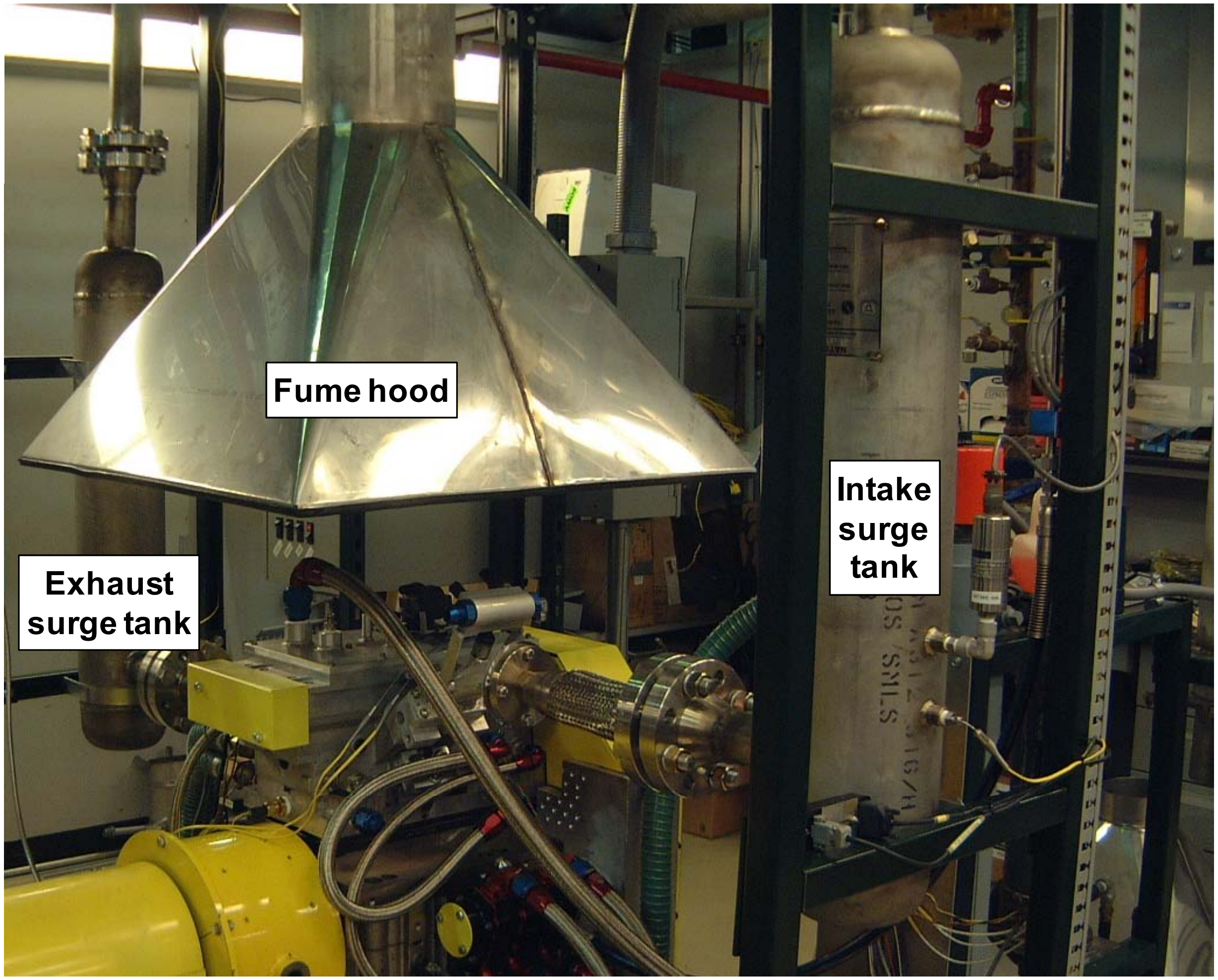
- **Ventilation**
  - No specific pattern due to highbay setting
  - Fume hood on top of engines to capture potential leakage
- **Sensors in strategic locations**
  - Inside fume hoods
  - Inside hydrogen distribution panel
  - Flame cameras on both engines

Fume hood design



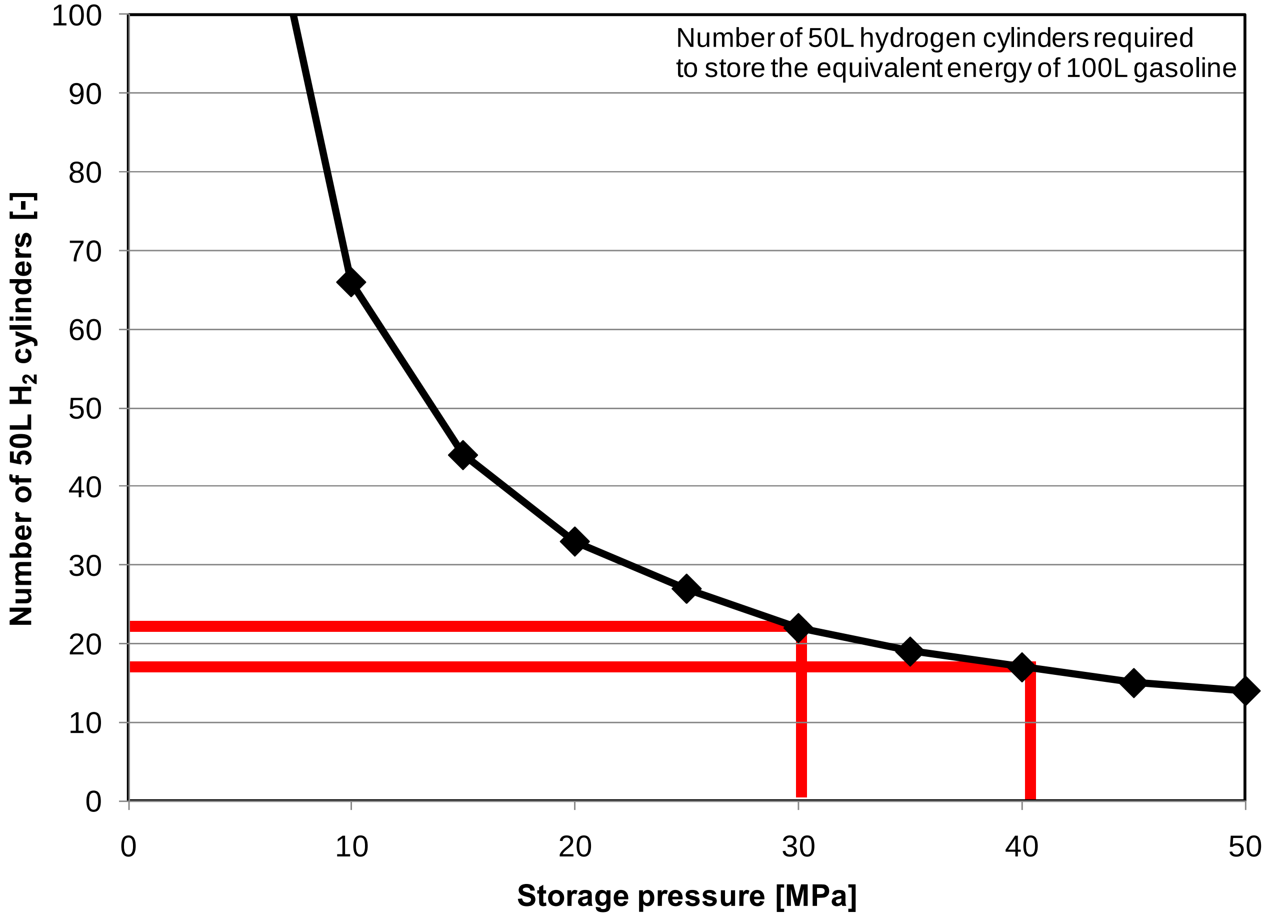
- **3-D CFD simulation to determine fume hood effectiveness**
  - Air flow 10 m/s
  - Square domain (2.2 m)
  - 150,000 cells
  - Several release scenarios simulated
- **Critical case**
  - Small leak around injector (0.2 kg/h)
  - High local concentration (100,000 ppm)
  - Concentration less than 2,000 ppm (5 % LEL) at sensor

Intake and exhaust design



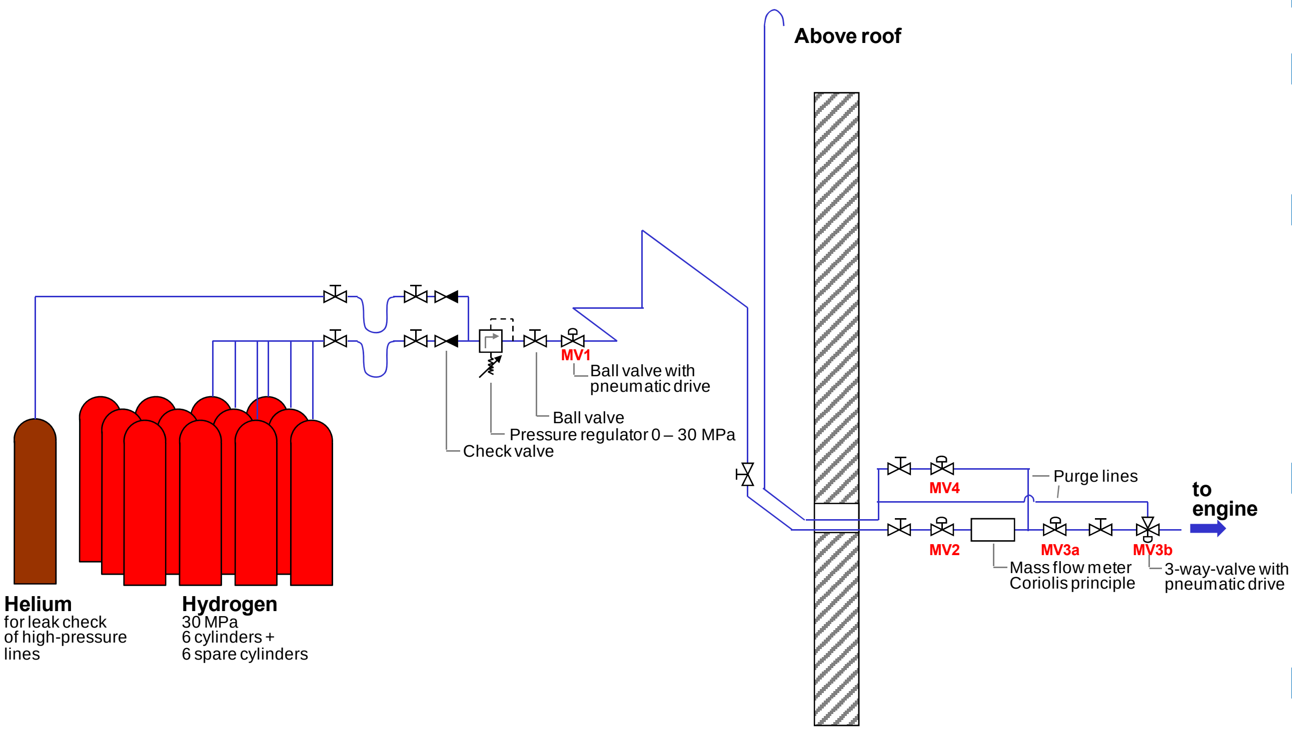
- **Special precautions for single cylinder research engine**
  - ASME rated pressure vessels in engine intake and exhaust
  - Reduce pulsations
  - Avoid damage should combustion anomalies occur

Compressed hydrogen storage capacity



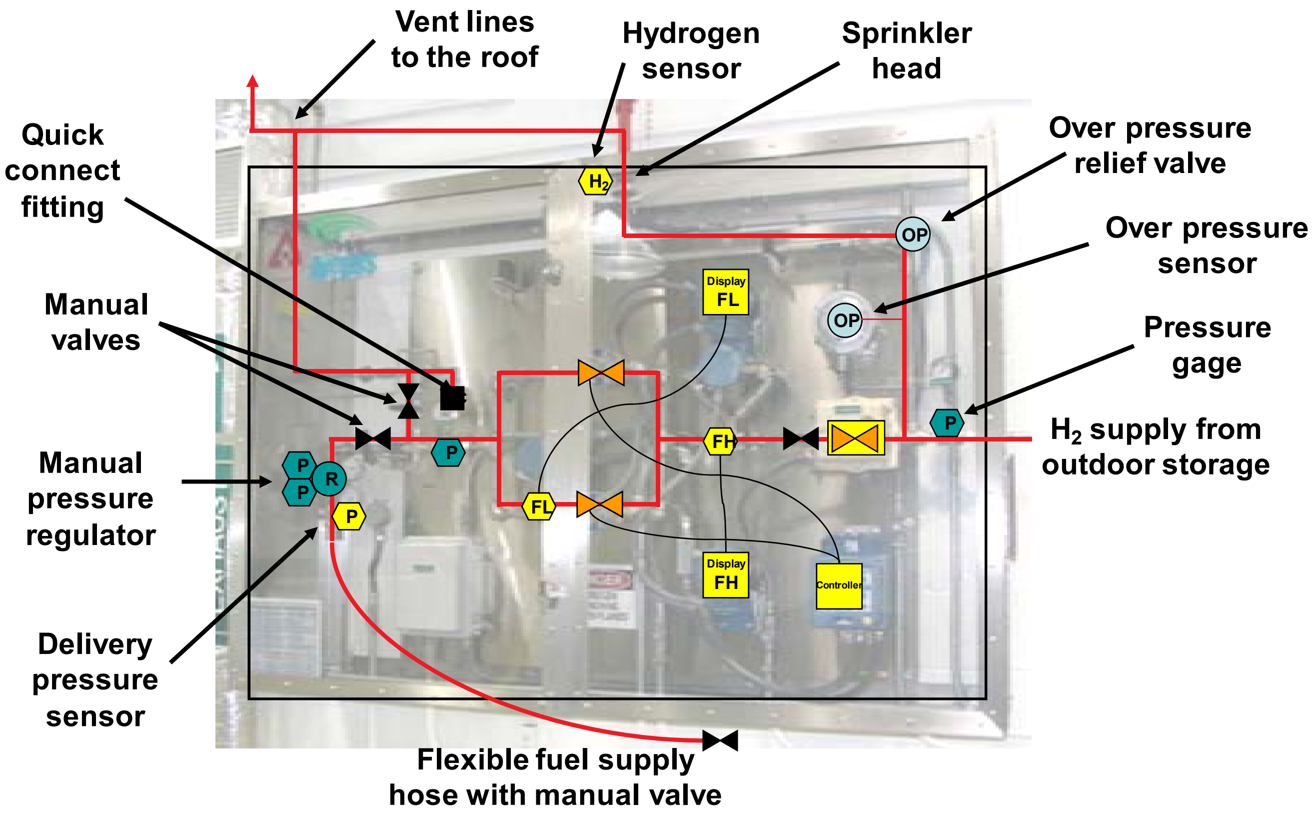
- **Number of cylinders required to store energy equivalent of 100 liters of gasoline**
- **Typical pressures**
  - EU: 20 – 30 MPa
  - US: 14 – 41MPa
  - Vehicle: 20/35/70 Mpa
- **Sample setups**
  - 6+6 cylinders at 30 Mpa
  - 2 cylinders at 41 Mpa

Sample high-pressure hydrogen supply system



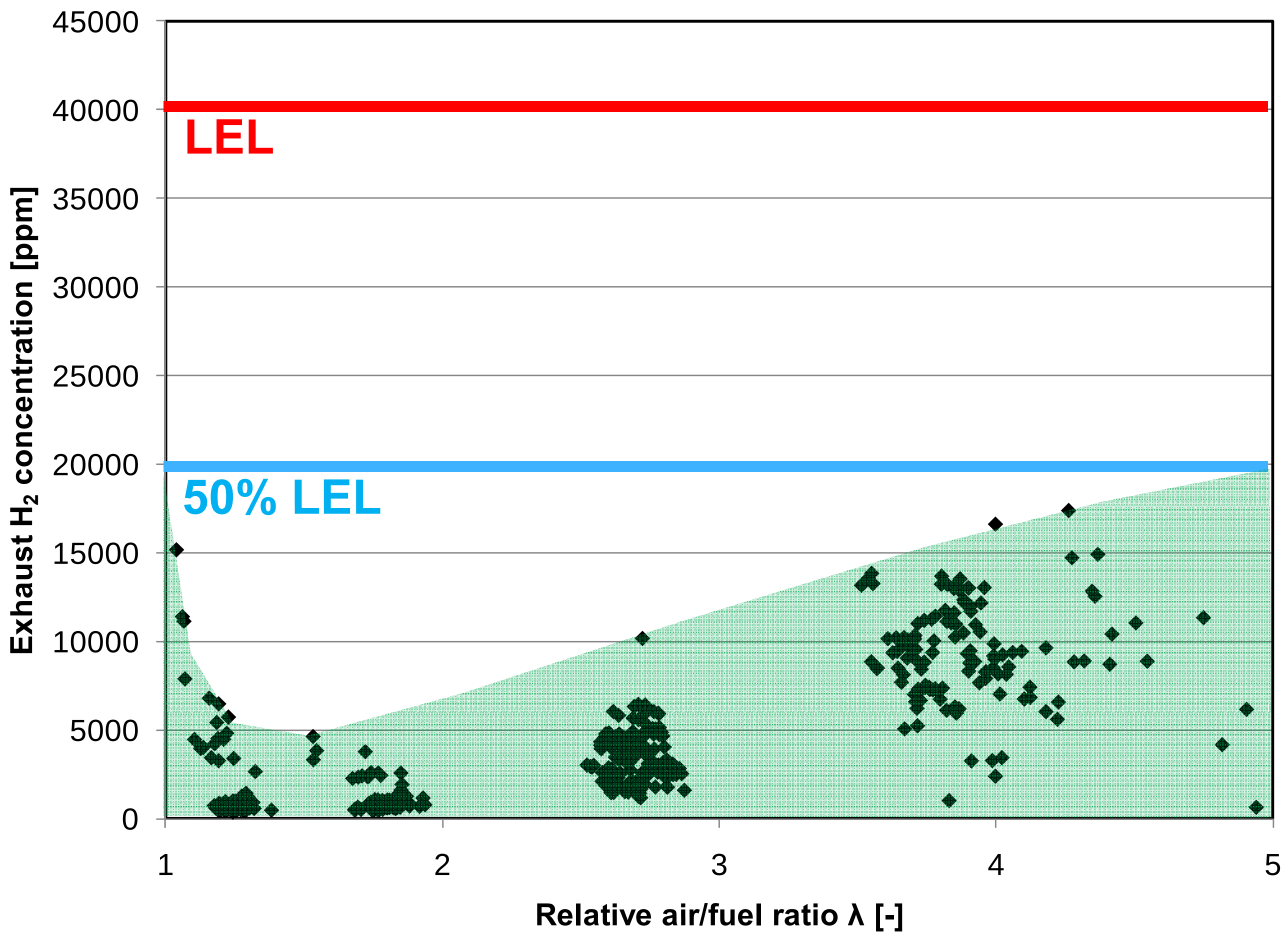
- 6+6 cylinders
- Helium for leak check/purge
- Pressure regulator outside to reduce hydrogen inside test cell
- Several solenoid valves (MV) with switching logic
- 3-way valve to depressurize engine supply line

Sample fuel meter and safety system



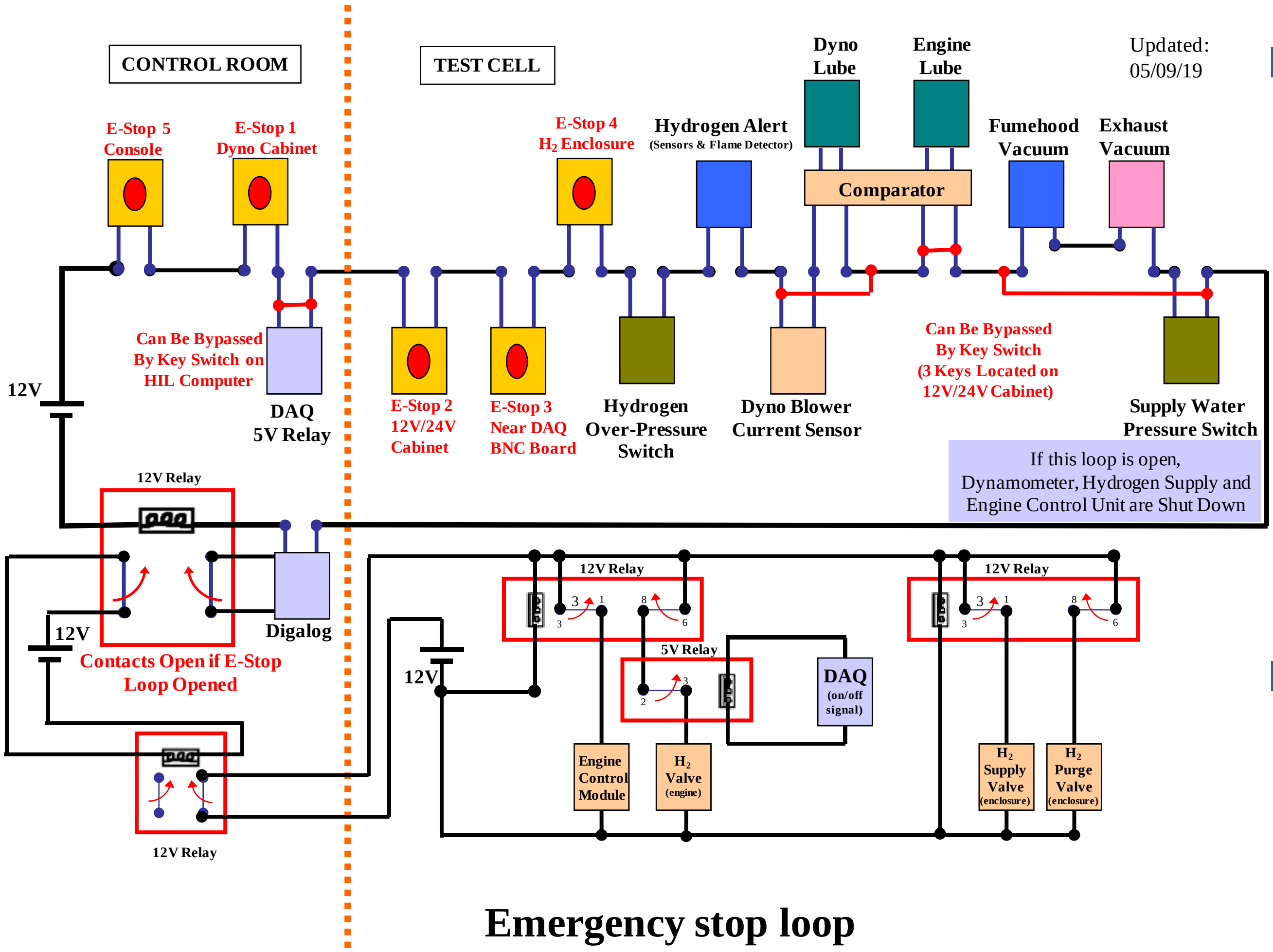
- **Fully enclosed hydrogen supply and metering system featuring:**
  - Pressure adjustment
  - Overpressure control
  - High and low flow fuel measurement
  - Vent lines to depressurize/purge
- **Opening on the top allows monitoring for leakage**

Exhaust hydrogen concentration



- **Sample results of unburned hydrogen in the engine exhaust**
- **Lower explosion limit for hydrogen: 4 %**
- **50 % LEL set as user defined limit**
- **Typical engine emissions trends:**
  - Increase around stoichiometry
  - Increase if operated extremely lean

Integrated safety system



Emergency stop loop

- **E-Stop loop specific for hydrogen:**
  - Fume hood air flow
  - Exhaust air flow
  - Hydrogen overpressure
  - Hydrogen alert (hydrogen sensor or flame camera)
  - DAQ monitors H2 flow, exhaust etc.
- **E-Stop disables:**
  - Dynamometer
  - Hydrogen supply
  - Engine controller (fuel injection)

Conclusions

- The properties of hydrogen differ significantly from those of other conventional liquid or gaseous fuels
- Ignition sources cannot be completely excluded from a test setup; therefore a safe test cell design effectively avoids build-up of ignitable hydrogen-air mixtures
- The unique instrumentation in a hydrogen test environment includes hydrogen sensors as well as hydrogen flame cameras. An additional factor of safety can be achieved by integrating and monitoring safety relevant functions in an emergency system
- When properly taking the unique properties into account by facility designers, engineers and operators, hydrogen can be as safe as, or safer than gasoline or diesel fuel

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