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Principles of inherently safer design of hydrogen vehicles for use in confined spaces

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Clean Hydrogen Partnership

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Hazards of HFCEV in confined spaces

associated with high-pressure hydrogen storage

- Momentum-dominated and large flow rate release from TPRD
- Momentum-dominated jet fire compromising
  - Safety of passengers, public and first responders,
  - Safety infrastructure including ventilation system
- Press-peaking phenomenon
- Hydrogen deflagration
- Hydrogen deflagration-to-detonation transition (DDT)
- Hydrogen high-pressure tank rupture
  - Blast wave, fireball, projectiles

Hydrogen release through TPRD (1/2)

TPRD parameters and direction of release should be designed to avoid:

- Flammable cloud formation under the ceiling of underground parking,
  - Excludes flammable cloud accumulation (above 4% vol. H_2)
  - Excludes potential deflagrations and DDT

Appendix 3. Hydrogen safety engineering models and tools

This appendix includes a brief description of models and tools, including references to their detailed description, for hydrogen safety engineering of systems, e.g. vehicles that can be useful for assessment of hazards and associated risks in underground traffic infrastructure. The models and tools allow assessment of hazards, incident consequences and could facilitate the development of prevention and mitigation strategies and innovative engineering solutions. They are built of the accumulated knowledge in hydrogen safety and results of experimental, numerical and theoretical studies, including within the HyTunnel-CS project.

A3.1 Tools for assessment of unignited hydrogen releases and jet fires

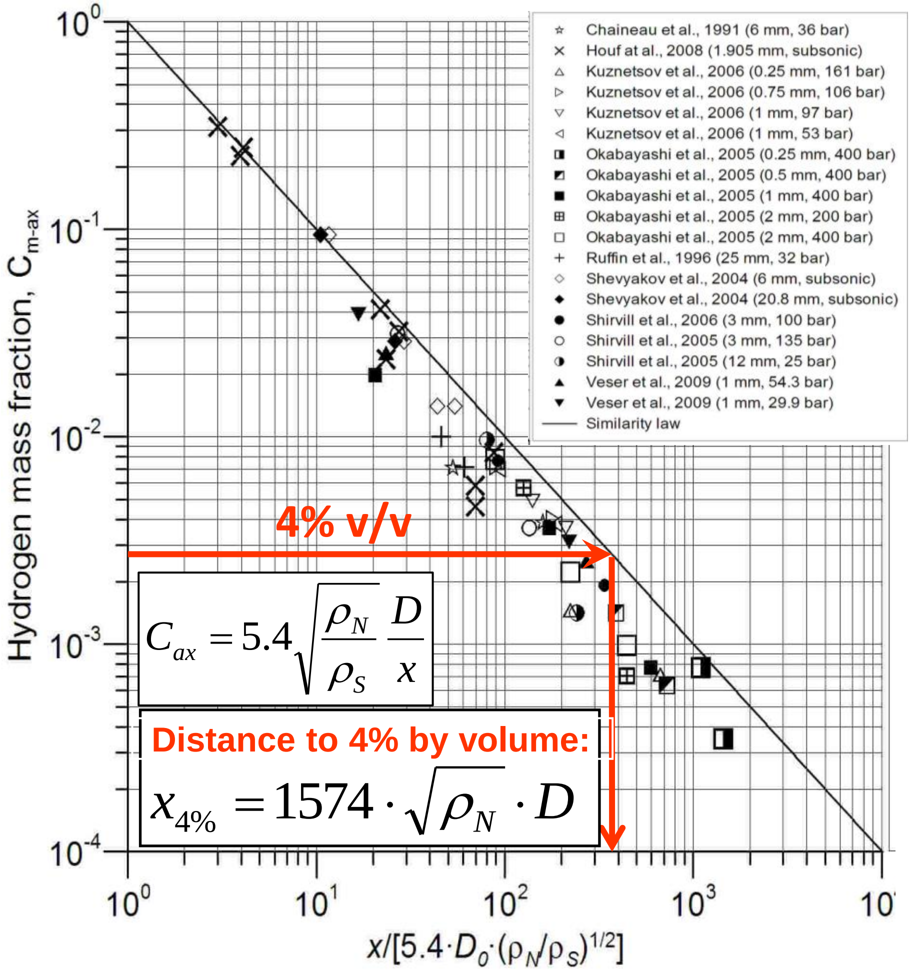
A3.1.1 The similarity law for concentration decay in momentum-dominated jets

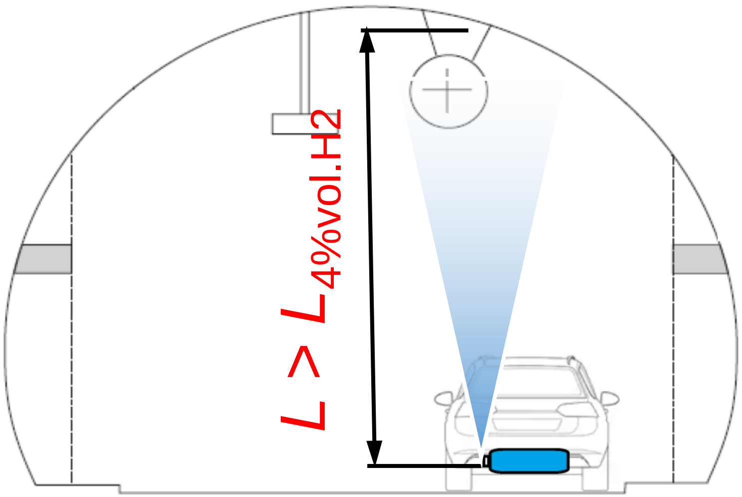
Releases from pressurised hydrogen storage and equipment will be in the momentum-dominated regime. Hydrogen concentration in buoyancy-controlled jets decays faster (Molkov, 2012) compared to momentum-dominated jets correlations which could be taken as a conservative estimate. The semi-empirical correlation for gaseous jet decay along the centre-line of a free, unobstructed **subsonic** jet was proposed by Chen and Rody (1980):

$$\frac{C_{ax}}{C_N} = 5.4 \cdot \sqrt{\frac{\rho_N}{\rho_S}} \frac{D}{x}, \qquad (1)$$

Hydrogen release through TPRD (2/2)

Exclusion of flammable mixture formation





Nozzle ∅, mm	5.0	1.0	0.5
P=350 bar, ρ_N=14.6 kg/m3			
$L_{4\%vol.H2}$, m	32.6	6.5	3.2
P=700 bar, ρ_N=24.6 kg/m3			
$L_{4\%vol.H2}$, m	42.0	8.4	4.2

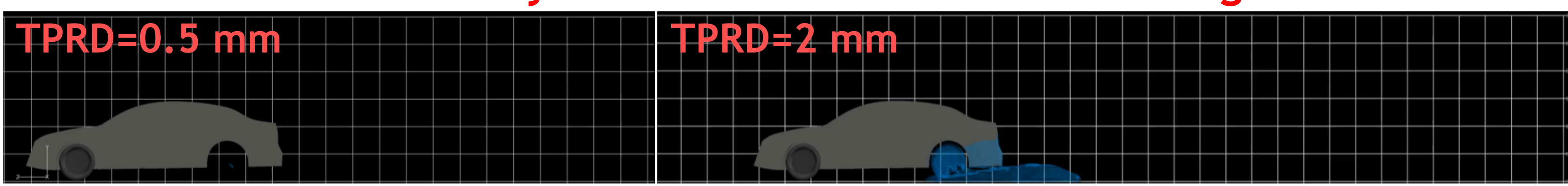
Ref.: V. Molkov "Fundamentals of hydrogen safety", 2012

Hydrogen jet fires

TPRD diameter reduction to:

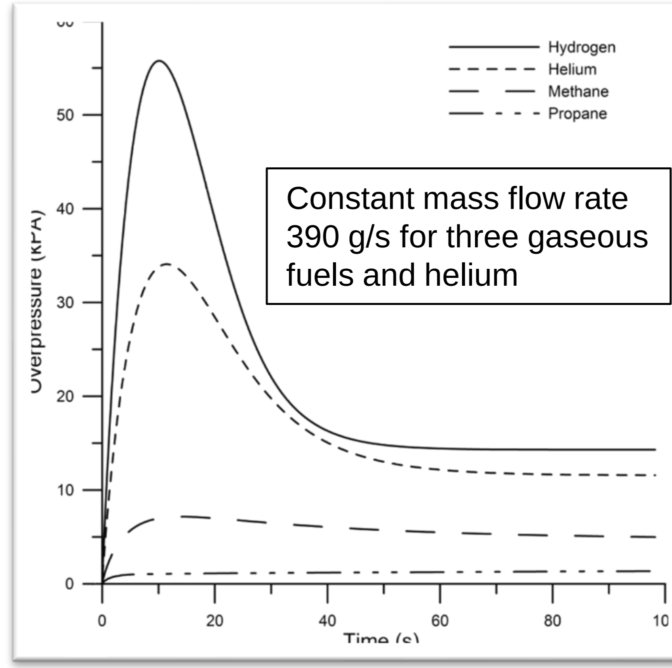
- Not compromise evacuation from HFCEV
- Not threaten public and operation of first responders
- Exclude temperature of 300°C under ceiling preventing damage to carpark ventilation

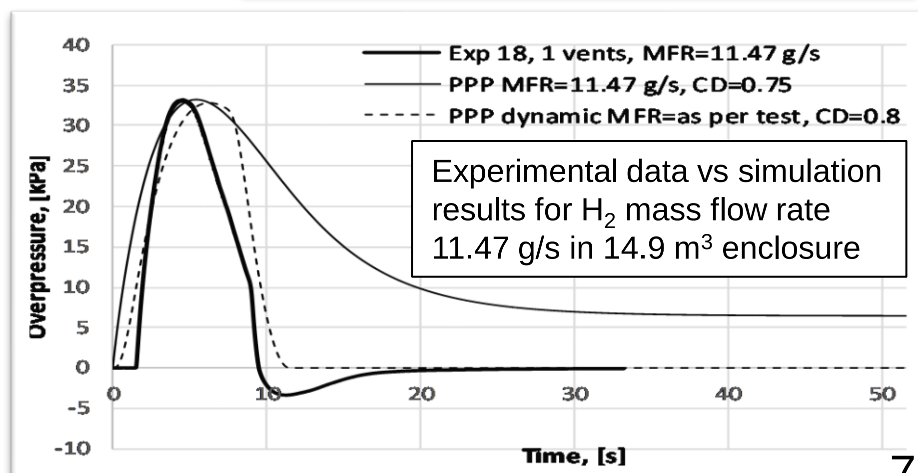
Fire from TPRD. Safety criterion: T<300°C under ceiling.



Pressure peaking phenomenon (PPP)

- Phenomenon unique for H_2 release
- Leads to pressure increase in poorly ventilated enclosure
- PPP is more hazardous for jet fires
- Mitigation by minimising release orifice
- Engineering and numerical tools are published and available





Hydrogen deflagration

Deflagrations and DDT potential can be excluded or mitigated by design of TPRD orifice diameter and release direction in a way that:

- No flammable cloud can be formed under the ceiling of carpark
- Flammable hydrogen inventory limit in a sealed enclosure doesn't lead to deflagration threatening live and property
- Hydrogen release does not lead to flammable mixture with fastest burning composition contributing to the largest deflagration overpressure
- Models and engineering tools are published and available

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Deflagrations of localised homogeneous and inhomogeneous hydrogen-air mixtures in enclosures

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ABSTRACT

Two original models for use as novel tools for the design of hydrogen-air deflagration mitigation systems for equipment and enclosures are presented. The first model describes deflagrations of localised hydrogen-air mixtures in a closed space such as a pressure vessel or a well-sealed building while the second model defines safety requirements for vented deflagrations of localised mixtures in an enclosure. Examples of localised mixtures include 'pockets' of gas within an enclosure as well as stratified gas distributions which are especially relevant to hydrogen releases. The thermodynamic model for closed spaces is validated against experiments available from the literature. This model is used to estimate the maximum hydrogen inventory in a closed space assuming the closed space can withstand a maximum overpressure of 10 kPa without damage (this is typical of many civil structures). The upper limit for hydrogen inventory in a confined space to prevent damage is found to be equivalent to 7.9% of the closed space being filled with 4% hydrogen. If the hydrogen inventory in a closed space is above this upper limit then the explosion has to be

Appendix 3.2 Tools for assessment of deflagrations, DDT and detonations

A3.2.1 Upper limit of hydrogen inventory in closed space without ventilation

A thermodynamic model (Makarov *et al.*, 2018) allows to estimate of maximum possible inventory of hydrogen that can be released in a large, closed space like warehouse and, if ignited … order … hydrog… The ov… combu… the e-L… in two…

A3.2.3 Venting of non-uniform hydrogen-air deflagrations

Realistic releases of hydrogen in confined spaces most often lead to formation of highly non-uniform, stratified hydrogen-air mixtures. Venting remains the most cost-effective deflagration mitigation technique. It was demonstrated that vented deflagrations of stratified hydrogen-air mixture may lead to significantly higher overpressure compared to the leaner uniform hydrogen-air composition with the same hydrogen inventory (HyIndoor, 2014) creating a need for a specially adopted vent sizing methodology for mitigation of localised hydrogen-air mixture deflagrations.

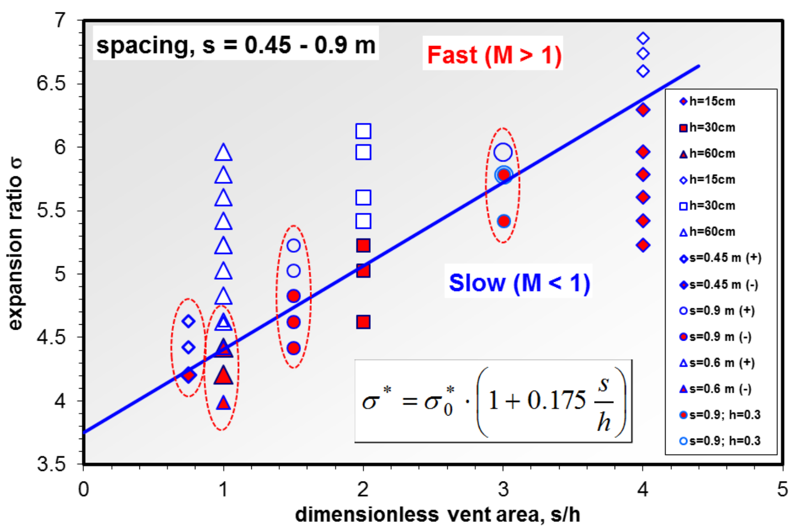
The vent sizing correlation for localised mixture deflagration in an enclosure was first developed theoretically (Molkov, 1996) and later validated against experiments performed in

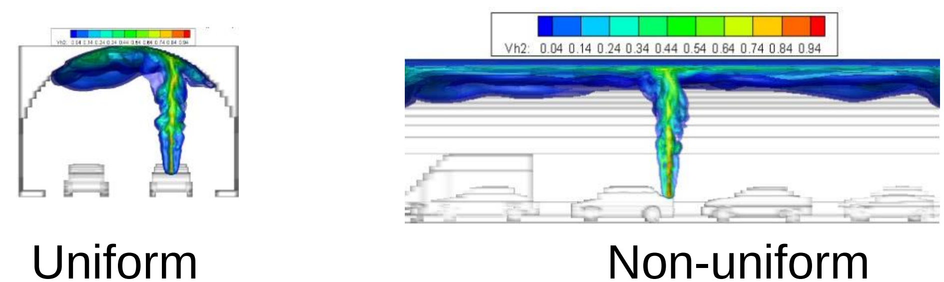
Deflagration-to-detonation transition

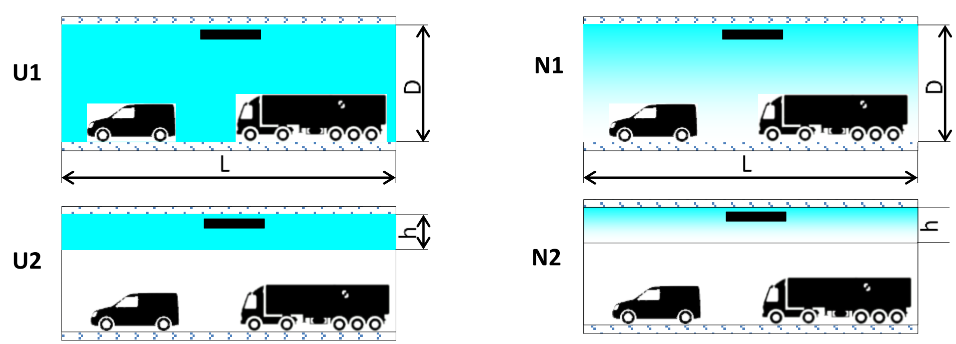
Tool for assessment of DDT potential

Correlation for assessment of DDT potential in hydrogen-air mixtures accounts:

- Characteristic reactivity
- Geometry
- Scale/dimension and non-uniformity of the hydrogen – air cloud
- Total hydrogen inventory
- Characteristic time (for hydrogen distribution and cloud formation)



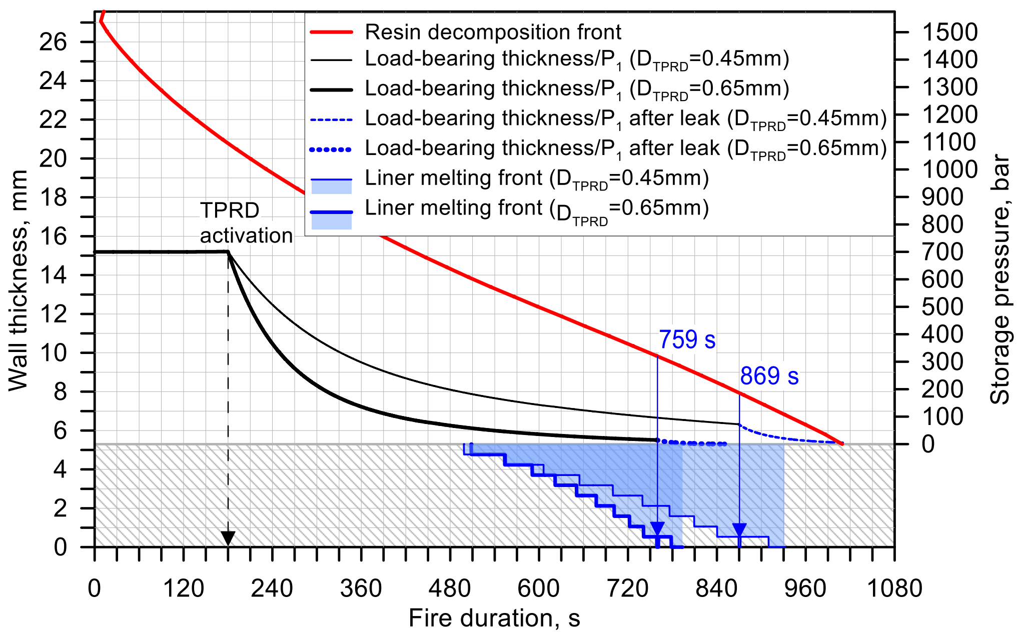




Tank rupture (1/2)

Tank-TPRD system design

- A model to calculate the lower limit for TPRD diameter that would exclude a tank rupture in an engulfing fire was developed within HyTunnel-CS project.
- The model is published and available to OEMs



Tank-TPRD system performance in a fire.
Tank 36 L, 70 MPa, TPRD ∅0.45mm and ∅0.65mm

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Performance of hydrogen storage tank with TPRD in an engulfing fire

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HIGHLIGHTS

- Non-adiabatic model of tank-TPRD system behaviour in fire conditions introduced.
- Under-expanded hydrogen jet theory based on Abel–Noble equation described.
- Liner melting phenomenon during blowdown through reduced TPRD diameter revealed.
- Innovative methodology of inherently safer tank-TPRD system design suggested.
- Dependence of tank fire-resistance rating on specific heat release rate presented.

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ABSTRACT

The performance of a composite hydrogen storage tank with TPRD in an engulfing fire is studied. The non-adiabatic tank blowdown model, including in fire conditions, using the under-expanded jet theory is described. The model input includes thermal parameters of hydrogen and tank materials, heat flux from a fire to the tank, TPRD diameter and TPRD initiation delay time. The unsteady heat transfer from surroundings through the tank wall and liner to hydrogen accounts for the degradation of the composite overwrap resin and melting of the liner. The model is validated against the blowdown experiment and the destructive fire test with a tank without TPRD. The model accurately reproduces experimentally measured hydrogen pressure and temperature dynamics, blowdown time, and tank's fire-resistance rating, i.e. time to tank rupture in a fire without TPRD. The lower limit for TPRD orifice diameter sufficient to prevent the tank rupture in a fire and, at the same time, to reduce the flame length and mitigate the pressure peaking phenomenon in a garage to exclude its destruction, is assessed for different tanks, e.g. it is 0.75 mm for

Tank rupture (2/2)

Explosion free in a fire TPRD-less tank

- Breakthrough safety technology (background IP)
- **Allows** hydrogen-powered vehicles and trains enter and park in **any confined space**
- **Excludes tank rupture** (tested in fires with HRR/A=1 MW/m^2 and its consequences – blast wave, fireball, projectiles, etc.

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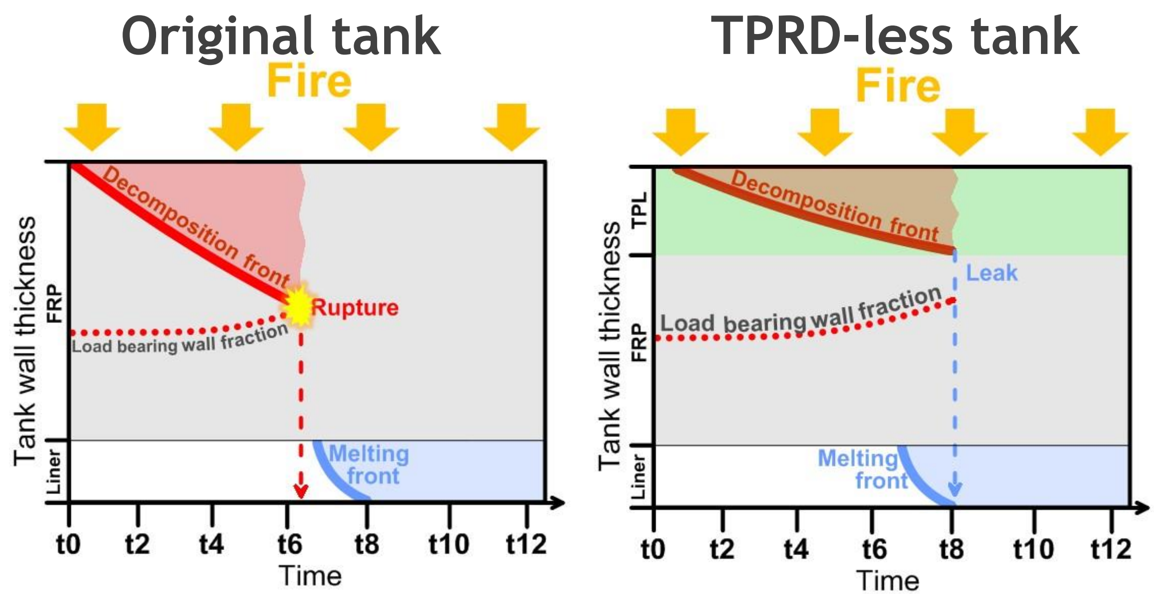

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Concluding remarks

- The largest hazards and risks in use of HFCEV in confined spaces are associated with the high-pressure onboard hydrogen storage in form of hydrogen releases, combustion, tank ruptures, etc.
- Safety solutions are numerous and depend on the particular accident scenario.
- The described safety strategy allows to reduce hazards and risks to the level comparable to that of conventional fuel vehicles and bring HFCEV to underground transport infrastructure satisfying the currently available RCS.

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