Guidelines for safe design and operation of LH_2 infrastructure

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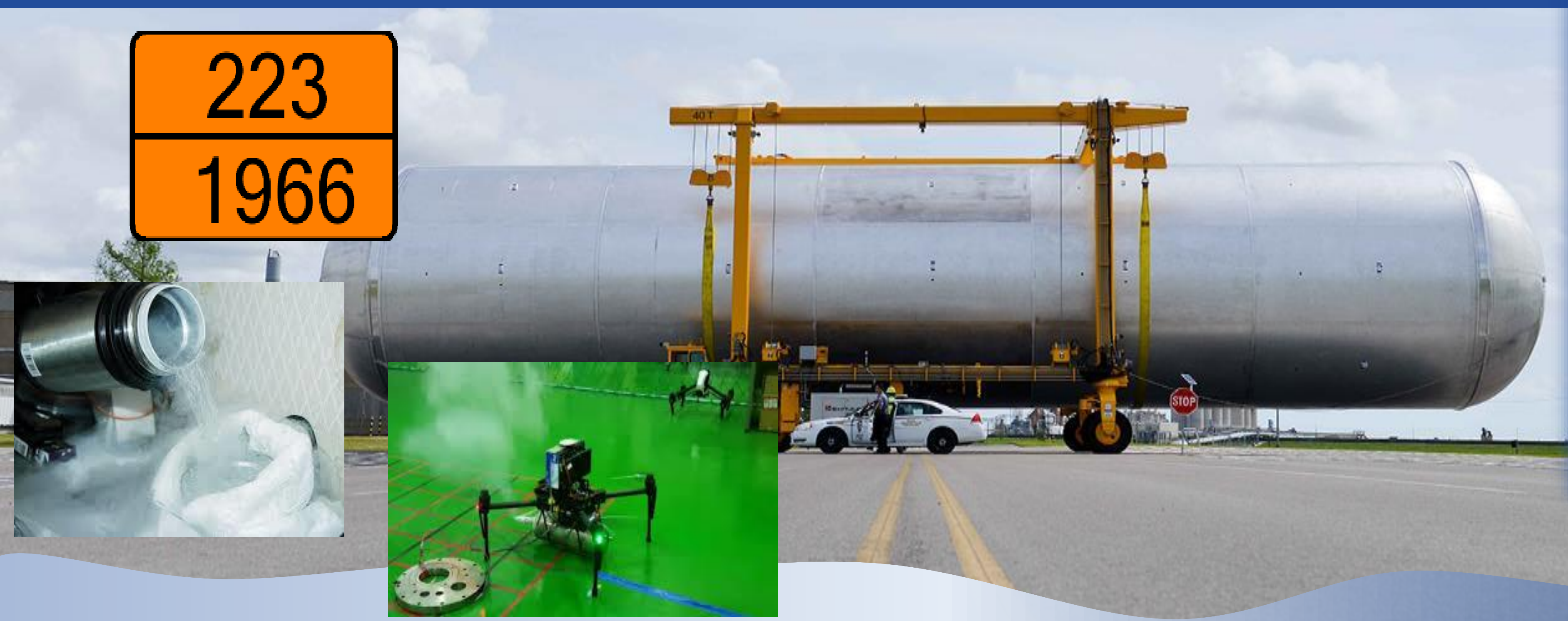
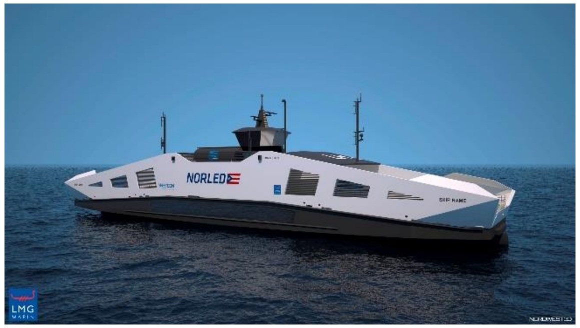
Pre-normative REsearch for Safe use of Liquid HYdrogen



Motivation

- Provide easy to use guidelines to engineers for the safe design and operation of liquid hydrogen (LH_2) infrastructure.
- Three main topics were addressed:
  - Cryogenic hydrogen release and dispersion,
  - Ignition of cryogenic hydrogen mixtures,
  - Combustion of cryogenic hydrogen.



- These topics were studied through:
  - A review of the existing state of the art and a ranking of the identified phenomena,
  - A large experimental program covering the prioritized phenomena,
  - The evaluation and validation of analytical and numerical approaches to assess these phenomena.

Main outcomes on cryogenic releases

Experiments

The main observations are:

- For both small and large-scale hydrogen releases, solid deposits formed at the nozzle likely due to freezing of moisture/air contents and on impingement on sensors. In the small-scale releases, large diameters lead to a high fraction of entrained particles in the jet.

- Pool formation occurred on all substrates tested. With increasing porosity of the substrate, a delay in the pool formation occurred.

- For established flow of horizontal releases, no rainout was observed and pools formed for vertically downward releases.

Main outcomes on cryogenic releases

Analytical tools

- Similarity law for concentration decay in momentum jets of cryogenic hydrogen.
- Non-adiabatic blowdown model for a hydrogen storage tank.
- A release model for steady state single / two-phase choked / expanded flow through a discharge line with variable cross section, accounting for friction and extra resistances.
- HyPond can be used to estimate the size of the liquid pool on the ground produced by a low-pressure spillage of liquid hydrogen.
- The last method allows us to determine the thermodynamic state when LH2 is mixed with ambient air.

Main outcomes on cryogenic releases

Numerical tools

- LES CFD approach can be used for the modelling of cryogenic hydrogen flow in a pipe accounting for the effect of conjugate heat transfer through the pipe wall, and the estimation of the resulting mass flow rate.

- A CFD model (ADREA-HF) has been validated for cryogenic dispersion and BLEVE.

- A CFD inter-comparison work for gaseous cryogenic under-expanded hydrogen blowdown releases led to the conclusion that more experiments are necessary to fully understand the phenomena involved in the release and measure the variables (concentration decay, arrival time, temperature) close to the nozzle.

Main outcomes on ignition of cryogenic H_2

Experiments

- There is a slight increase in MIE for cryogenic hydrogen in comparison with ambient temperature for the same hydrogen concentration in air.
- In small pressurized cryo jet experiments (with cold H_2 and LH_2), strong electrostatic fields were measured but no spontaneous ignition was recorded.
- In large-scale cold cloud experiments, the flow of LH_2 in pipes causes electrostatic charges.
- No spontaneous ignition was noted above the pool.
- The tests performed with sprinklers and water jets did not generate Rapid Phase Transition (RPT). However, the rate of vaporisation is enhanced and if the cloud ignited it could lead to a larger fireball

Main outcomes on ignition of cryogenic H_2

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Analytical tools

- The analytical model can be used to assess the potential of cryogenic hydrogen-air mixtures to ignite.

Numerical tools

- CFD modelling can be used to investigate the potential of LH_2 evaporating pools to form mixtures of cryogenic hydrogen and condensed oxygen for different wind conditions.
- CFD modelling can be used to accurately predict MIE by spark ignition for hydrogen-air mixtures.
- CFD modelling can be applied to determine the limit storage pressure leading to spontaneous ignition of a hydrogen release at cryogenic temperature in a T-shaped channel.

Main outcomes on combustion of cryogenic H_2

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Experiments

- The jet fire experiments allowed better understanding of transient jets and combustion processes.
- Flame acceleration in cryogenic mixtures is determined by an increase in critical and effective expansion ratios. The run-up distance for detonation transition was reduced in cryogenic mixtures due to density effects.
- Release and ignition in an obstructed area:

    - For low levels of congestion, the risk of uncontrollable flame acceleration is low.

    - For high levels of congestion, it is appropriate to assume that a high-level explosion or DDT could occur.

Main outcomes on combustion of cryogenic H_2

Analytical tools

- Laminar burning velocity and expansion ratios for hydrogen-air mixtures.
- Correlation for cryogenic gaseous hydrogen jet flames length.
- Thermal load from hydrogen jet fires
- Maximum pressure load from delayed ignition of turbulent hydrogen jets
- Flame acceleration and detonation transition for cryogenic hydrogen-air mixtures
- Fireball size after liquid hydrogen spill combustion

Numerical tools

- CFD approach can be used to assess hazard distances for horizontal jet fires with inclusion of the buoyancy effect on high temperature combustion products and hot currents.

- CFD approach can be used to assess the effect of cryogenic storage temperature on PPP from ignited hydrogen releases.

Guidelines (1)

- Rainout can not be ruled out as a credible scenario for the moment.
- These results show that the use of gravel as ground material for filling stations should be reconsidered.
- The same safety measures as for ambient hydrogen-air mixtures may be employed regarding ignition.
- It is advised to design LH_2 pipework to limit the development of two-phase flows and ensure that the pipework contains no electrically isolated sections.
- Sprinklers and water jets can be employed as mitigation measures to control the flow or accumulation of LH_2.
- The run-up distance for detonation transition was reduced in cryogenic mixtures due to density effects but the influence of blockage ratio on cold mixtures DDT is less pronounced.

Guidelines (2)

- For risk assessment of a release in an obstructed area:
    - For low levels of congestion, the risk of uncontrollable flame acceleration is low. An assumption of TNO level 5 would be conservative to be applied to the cloud within the congested area.
    - For high levels of congestion, it is appropriate to assume that a high-level explosion or DDT could occur.
    - It might be appropriate to assume that a severe explosion could occur for intermediate levels of congestion. However, some additional experimental work is required to determine with more precision the boundary beyond which severe explosions happen.
    - As a rule of thumb, if all of the cloud could be in the congested area, the explosive energy release for 1 bar tanker pressure would be approximately 20MJ and for 5 bar pressure 50MJ.

Guidelines (3)

Calculation means for design and consequences assessment:

- Tools for calculation of the release flow rate can be used to design pipings;
- The similarity law can be used to determine the distance to LFL;
- The correlation for hydrogen jet flames can be used to estimate a cryogenic gaseous hydrogen jet fire flame length and associated hazard distances;
- The engineering tool for cryogenic hydrogen jet fire can be used to estimate the thermal radiative heat flux and thermal dose in the surroundings and associated hazard distances;
- An engineering tool for hydrogen jet fire can be used to estimate the maximum overpressure that can be expected from its delayed ignition and associated hazard distances;
- A correlation for spills can be used to determine a fireball size after liquid hydrogen spill combustion;
- A CFD approach can be used to assess hazard distances for horizontal jet fires with inclusion of the buoyancy effect.

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