
# Designing an inherently safe $H_2$ infrastructure:

## Combining analytical, experimental, and numerical investigations to optimize $H_2$ refueling stations safety by passive mitigation

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# Context

# Context & Objectives

## Context

**Clean Hydrogen** and **Fuel Cell Electric Vehicles** (FCEV) have developed significantly in the past years in order to respond appropriately to the challenges associated with the **transition to a Net-Zero Carbon Economy**

Associated infrastructure, in particular, **Hydrogen Refueling Stations** (HRS) were also developed to respond to the **increasing needs for Hydrogen in the mobility** sector

## Challenges

The need to mainstream Hydrogen in the mobility sector requires **higher levels of accessibility of HRS** in the **public environment**

Thus, it is necessary to **deploy inherently safe hydrogen refueling stations** without increasing **footprint** of such infrastructure because of excessively **drastic safety distances and barriers**

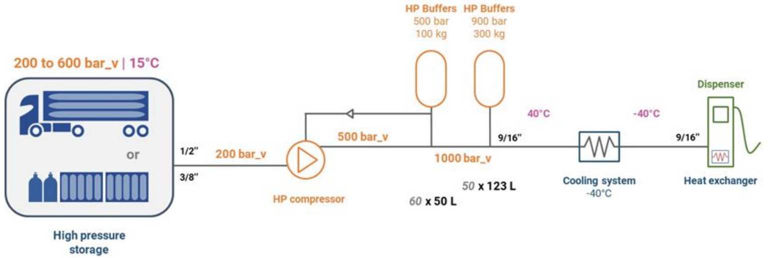
## Study objectives

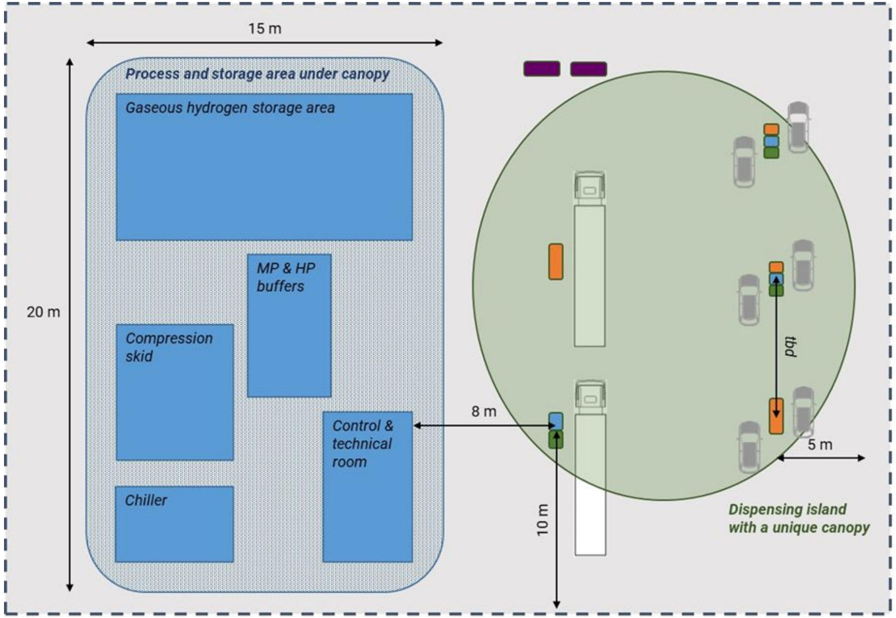
Combine **design**, conception and **aesthetic** of HRS for a **better integration in urban environment**

⇒ while keeping **safety consideration as the top priority**

# Gas-to-Gas $H_2$ Refueling Station

## *Generalities & Scope of the study*

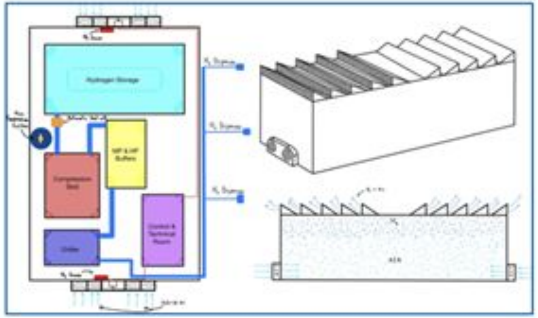



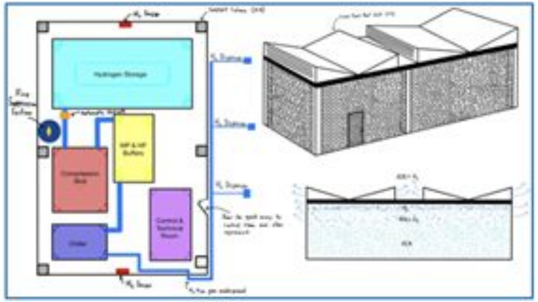

- **Focus on confined parts of the HRS**
  - Processing container
  - Dispenser

# Design concepts

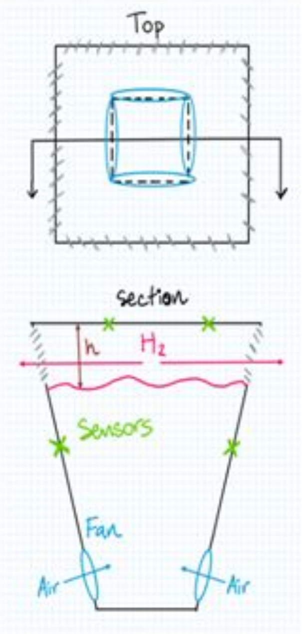
*Ideation*

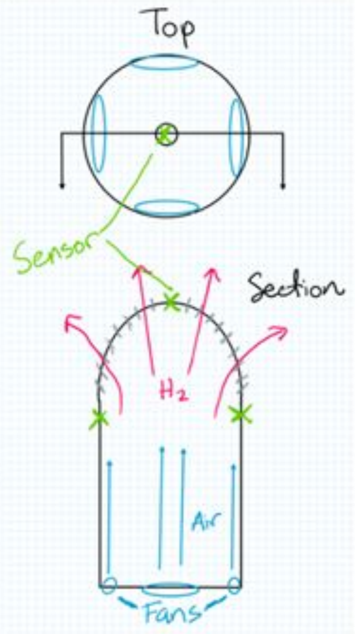
## Processing container

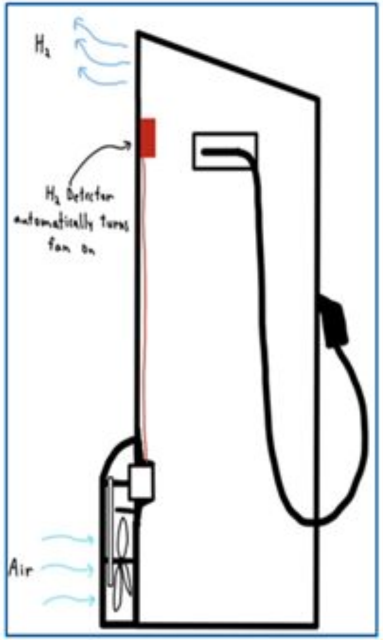




## Dispenser



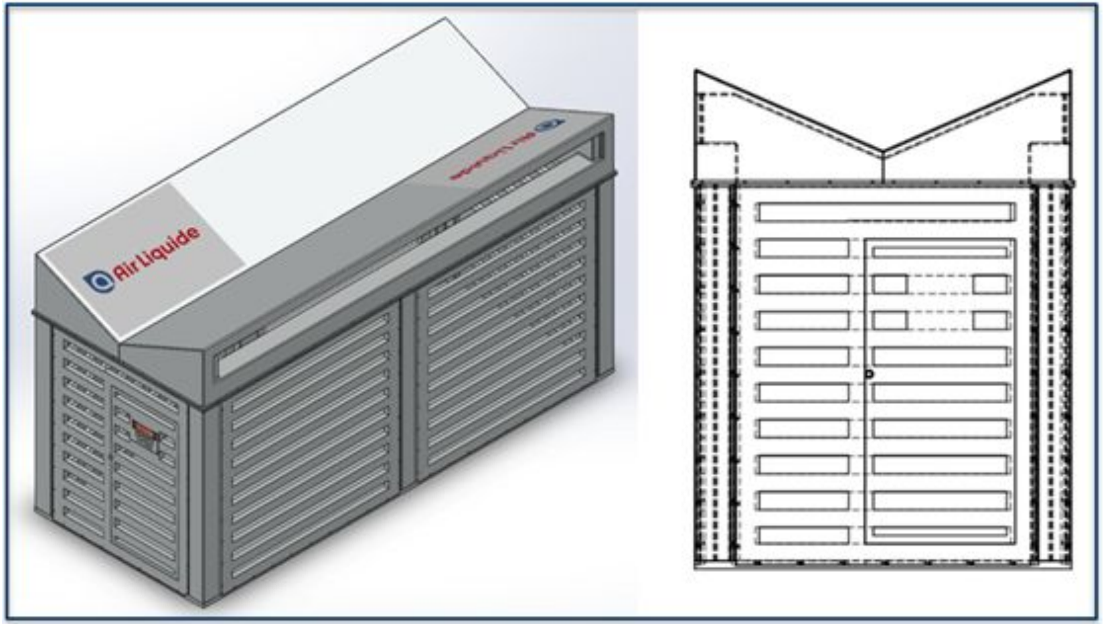



# Concepts retained

## *Criteria & Final choice*

- **Criteria**
  - significantly different from existing
  - assessable concept
  - not too much costly
  - easy-to-deploy
  - time-to-market considerations



**Processing container** → ***louvered walls and v-shaped roof***

**Dispenser** → ***conical***

# How to assess Risk & Safety of the concepts?

# Concrete cases

## *Risk analysis & consequences assessment - Methodologies and generic calculations*

1 Description of the studied case

2 Hazard identification

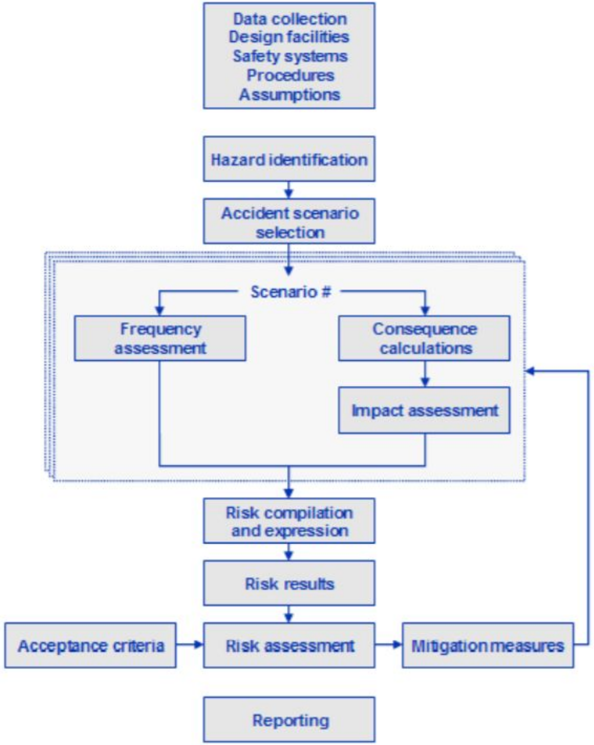
3 Severity assessment

4 Interpretation & Mitigation

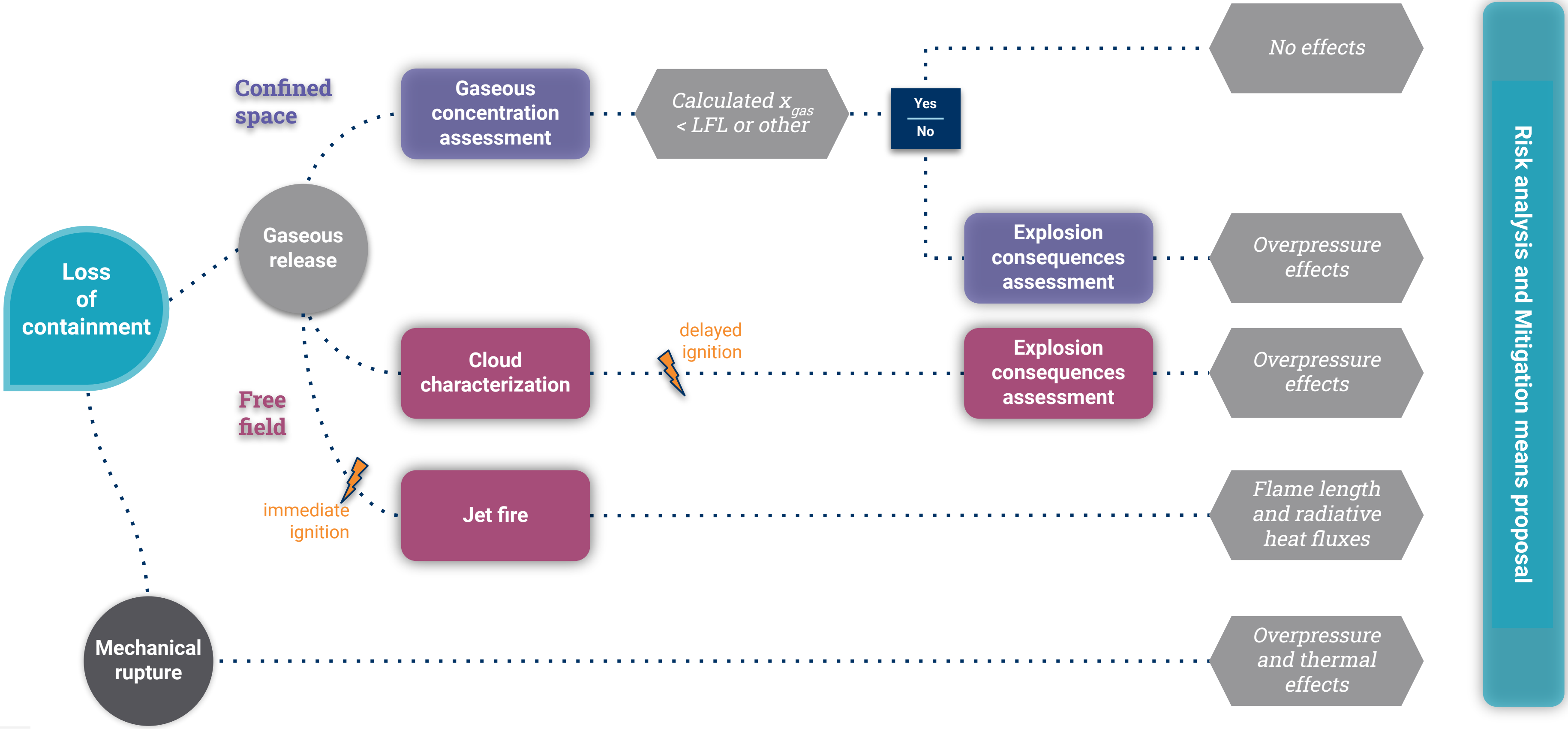
5 Final design

***Potential safety requirements in RCS, but:***

- ***no specification on how to assess the severity of a feared event***
- ***and rarely definition on methods/means to respect these requirements…***



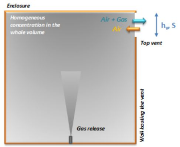
# Identification of the phenomena and associated consequences

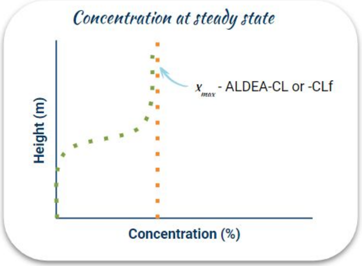


# Manage internal accidental releases

## *Smart natural ventilation*

*Ventilation through one opening Mixing regime*




*Build-up*

**Confined space**

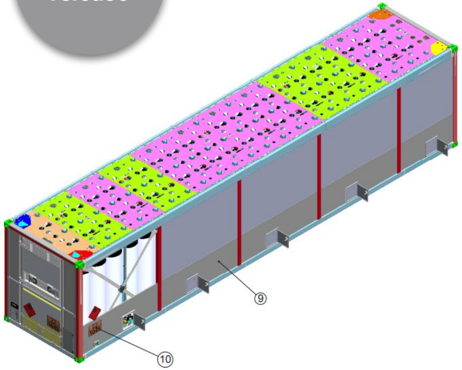
**Gaseous release**

**Gaseous concentration assessment**

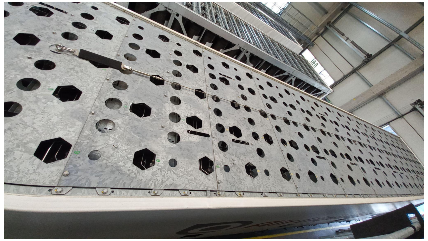
*Calculated $x_{gas}$ < LFL or other*

**Yes** → *No effects*

**No** → **Explosion consequences assessment** → *Overpressure effects*




*Explosion*



*Smart design*

Perforated roof for natural ventilation

# Means for Severity assessment of feared events

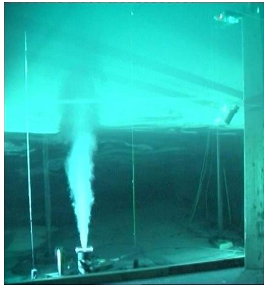
# Existing assessment means

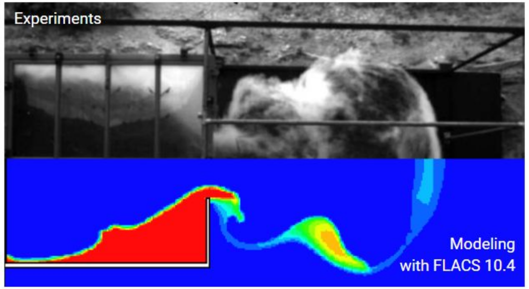
## *Non-exhaustive list*

- **Complementary approaches**
  - **Analytical modelling** | *HyRAM, PHAST, e-laboratory, non-public tools… (ALDEA for AL)*
    For quick and simple calculations
  - **Numerical simulations** (CFD) | *FLACS, FLUENT…*
    For complex geometries and scenarios, numerical experiments, extrapolation
  - **Experiments** | *Several test facilities and collaborative platforms*
    For validation and specific scenarios

**and… Define and Evaluate mitigation means**

- Concepts, Equipment, Protocols…





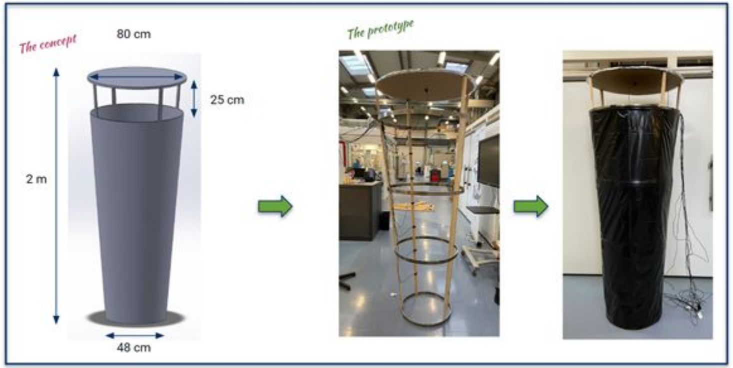

e-laboratory

HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models

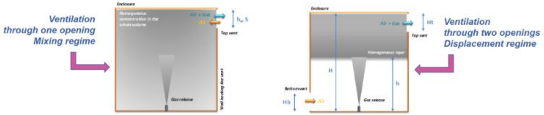

# Evaluation
# of dispenser concepts

# Dispenser concept

## *Studied cases*

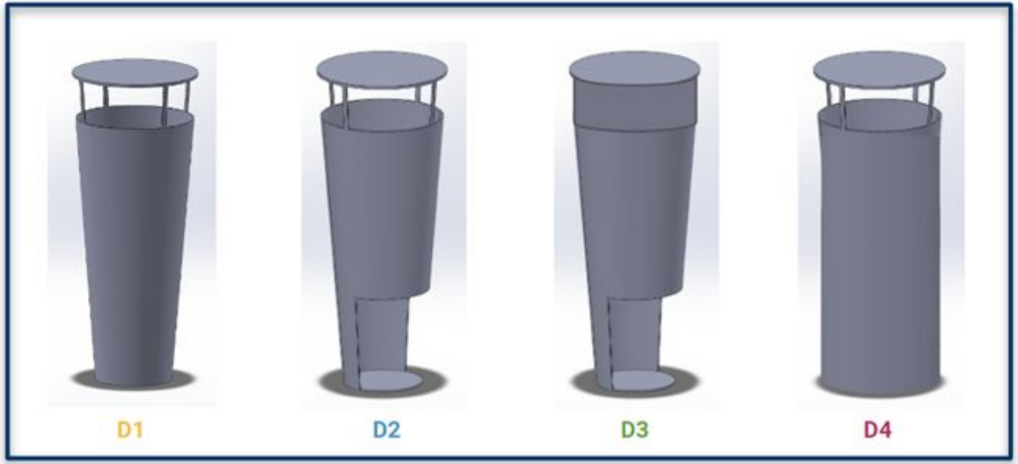



- **Method**
  - **Pre-calculations with analytical approaches** to size the Dispenser mock-up (Linden 1999)



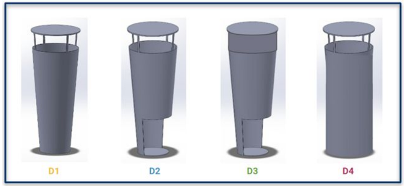

  - **Build-up experiments** with natural ventilation Concentration distribution thanks to minicatharometers in **near-real scale mock-up**
    - with He flow rates from 5 to 100 $NL.min^{-1}$
    - for different variants of the design


  - **Extrapolation** with **numerical simulations**
    - for 120 $g.s^{-1}$ which is commonly the maximum flow rate in a dispenser



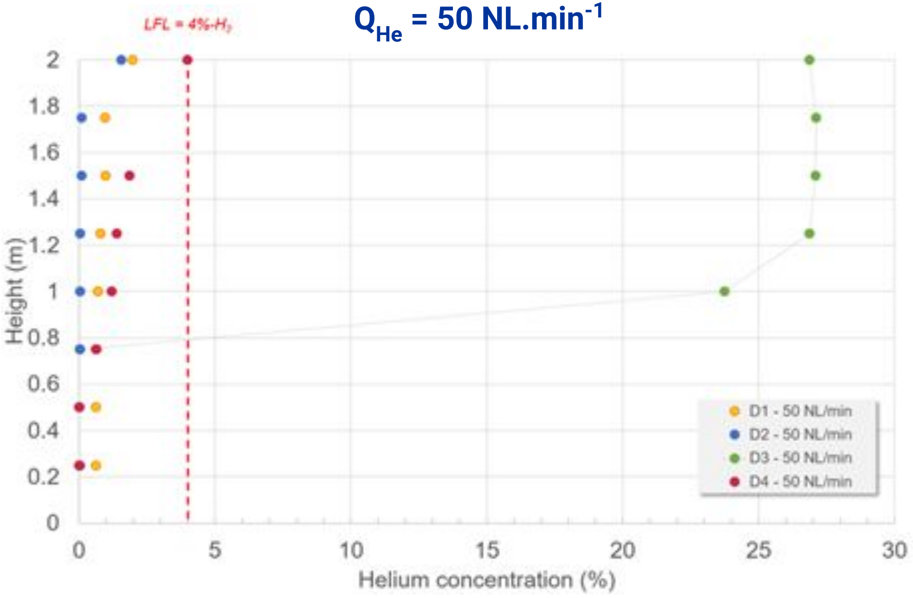
# Dispenser concept

## *Experimental results*

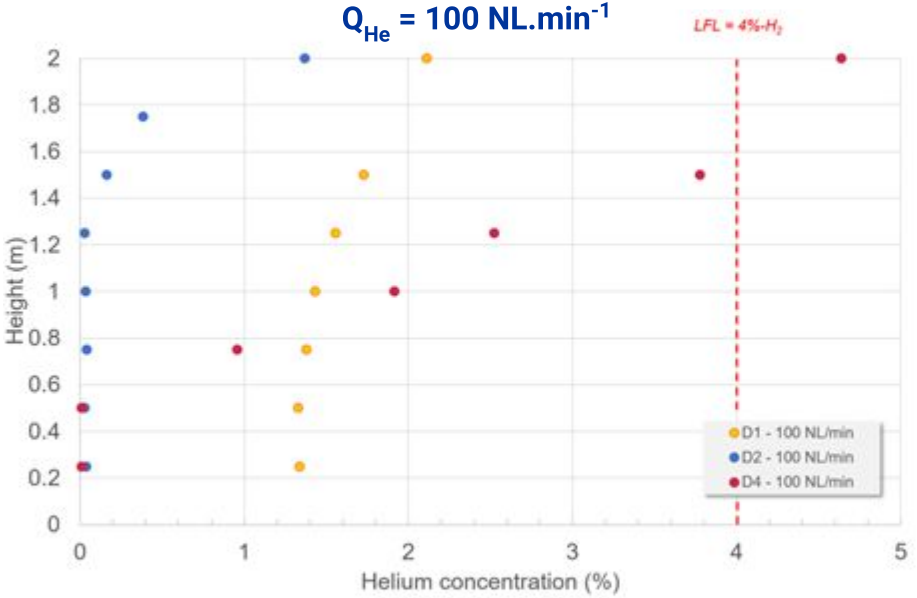



- **Design comparison** → for 50 and 100 NL.min$^{-1}$
  Concentration profiles at steady state

**$Q_{He}$ = 50 NL.min$^{-1}$**



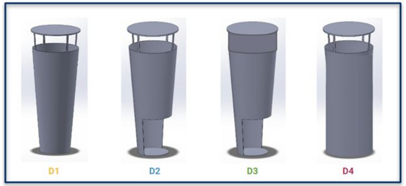

**$Q_{He}$ = 100 NL.min$^{-1}$**




⇒ Ventilation mode and design of **D2-dispenser give the best performances**, i.e. the lowest concentrations, contrarily to D3-dispenser

# Dispenser concept

## *Overview of experimental measurements vs analytical calculations*




- **Maximum concentrations** → from 5 and 100 NL.min$^{-1}$ **at steady state**

| Release flow rates | | 5 NL.min$^{-1}$ | | 50 NL.min$^{-1}$ | | 100 NL.min$^{-1}$ | |
|---|---|---|---|---|---|---|---|
| *Approach* | | *Exp.* | *Linden* | *Exp.* | *Linden* | *Exp.* | *Linden* |
| D1-dispenser |  | 0.8% | 0.5% | 2% | 2.4% | 2.3% | 3.8% |
| D2-dispenser |  | 0.7% | 0.3% | 1.3% | 1.4% | 1.4% | 2.3% |
| D3-dispenser |  | 6.3% | - | 26% | - | 36% | - |
| D4-dispenser |  | 0.8% | 0.8% | N/A | 2.4% | 4.5% | 5.6% |

⇒ At **highest flow rates**, **Linden** approach **over-predicts maximum concentration**
For same ventilation areas, **conical shape (D1) is more efficient** than cylindrical dispenser (D4)

# Dispenser concept

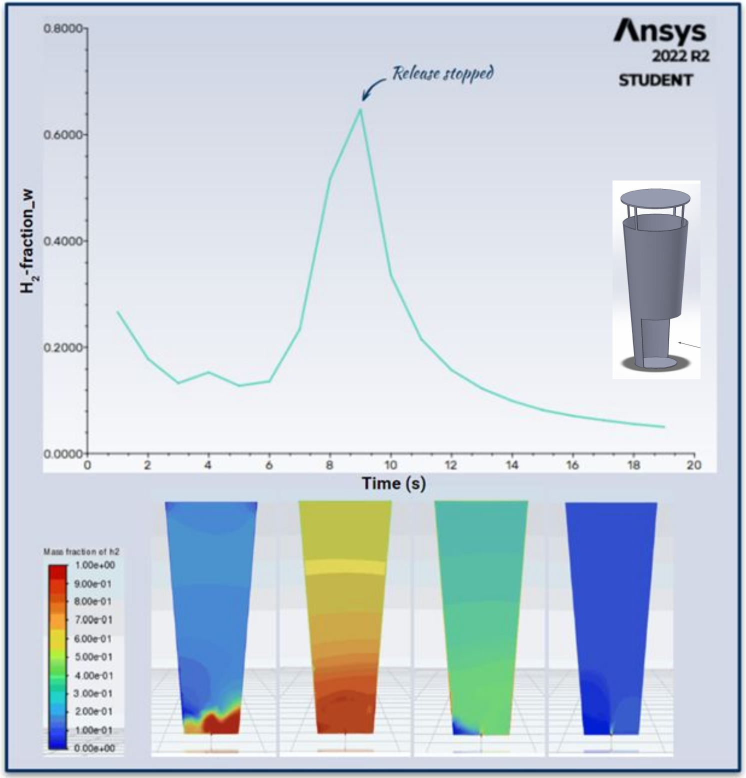
## *Extrapolation with numerical calculations*

- **Preliminary investigations with D2-dispenser for 120 g.s$^{-1}$ release rate**
  - **30%-$H_2$ is largely exceeded**
  - **However, if the release is stopped, acceptable concentration levels are found in 10 s**
  - **In case of ignition at stoichiometry (30%-$H_2$), considering ventilation opening as explosion venting panels, maximum internal overpressure would be lower than 50 mbar (calculated by Molkov et al. approach (1999)) → inducing deformation of the dispenser but no destruction, and no or limited fragments**

    *(coming… interesting experiments on ignition of flammable mixtures in a dispenser led by HSE in the framework of MultHyFuel project)*

⇒ **These results are very preliminary and will be refined for the next steps of this collaborative research work**

- **Need of more validation, a better calibration of the numerical model and associated parameters with an expert**



# Evaluation

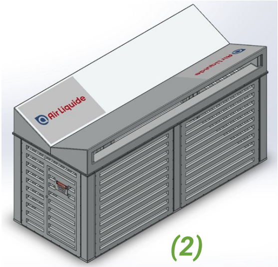
# of processing container concepts

# Processing container concept

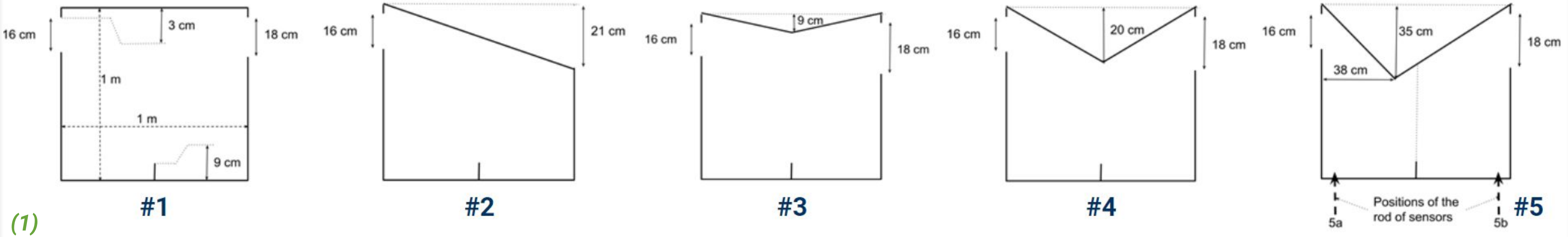
## *Studied cases*

- **Back to the concept**
  - **Roof inclination** & **Louvered walls** for natural ventilation and build-up mitigation

- **Method**
  - **Investigations in two-steps:** first on **roof inclination** *(1)*, and after combination of **inclined roof and louvered walls** *(2)*
  - **Build-up experiments** with natural ventilation
    Concentration distribution thanks to minicatharometers in a 1-$m^3$ enclosure
    - with He flow rates from 5 to 100 $NL.min^{-1}$
    - for different variants of the design
  - Experimental investigations on visualization of ventilation fluxes paths
    - with immersed down scaled mock-up - Archimedes number approach
    - with smokes outside the enclosure
  - **Further investigations** with **SimScale online numerical tool**




*(2)*




*(1)*

# Processing container concept

## *Experimental measurements* | *Roof inclination*

- **Maximum concentrations in a 1-$m^3$ enclosure** → **from 5 and 100 $NL.min^{-1}$ at steady state**

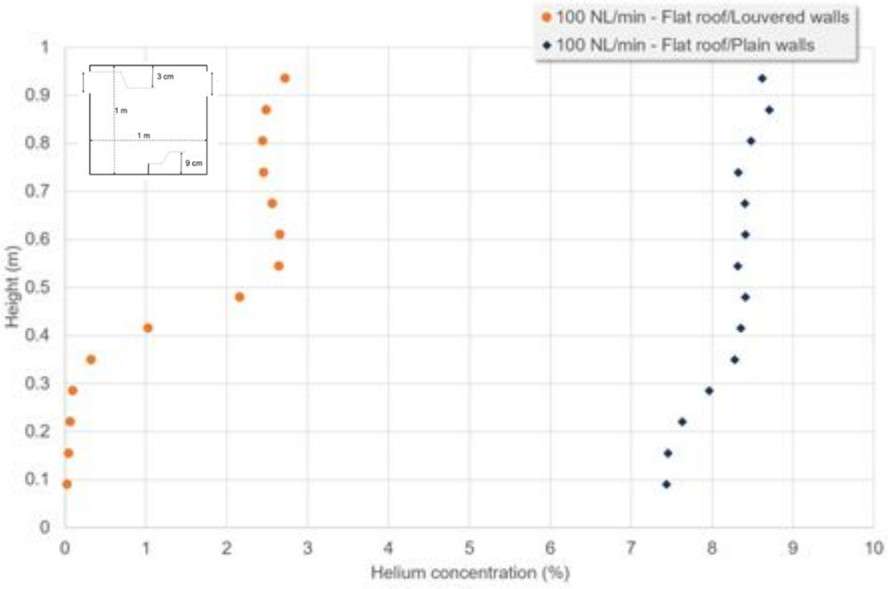
| Release flow rates | | $5\ NL.min^{-1}$ | $20\ NL.min^{-1}$ | $50\ NL.min^{-1}$ | $100\ NL.min^{-1}$ |
|---|---|---|---|---|---|
| Configuration 1 | 0% | 1.4% | 2.5% | 4% | 8.5% |
| Configuration 2 | | 1.6% | 3.8% | 7% | 14% |
| Configuration 3 | 18% | 0.8% | 2.1% | 3.9% | 7.5% |
| Configuration 4 | 40% | 0.8% | 2% | 3.5% | 4.5% |
| Configuration 5a | *a* *b* | 0.3% | 1.4% | 3% | 1.5% |
| Configuration 5b | | 1% | 2.3% | 5% | 6% |

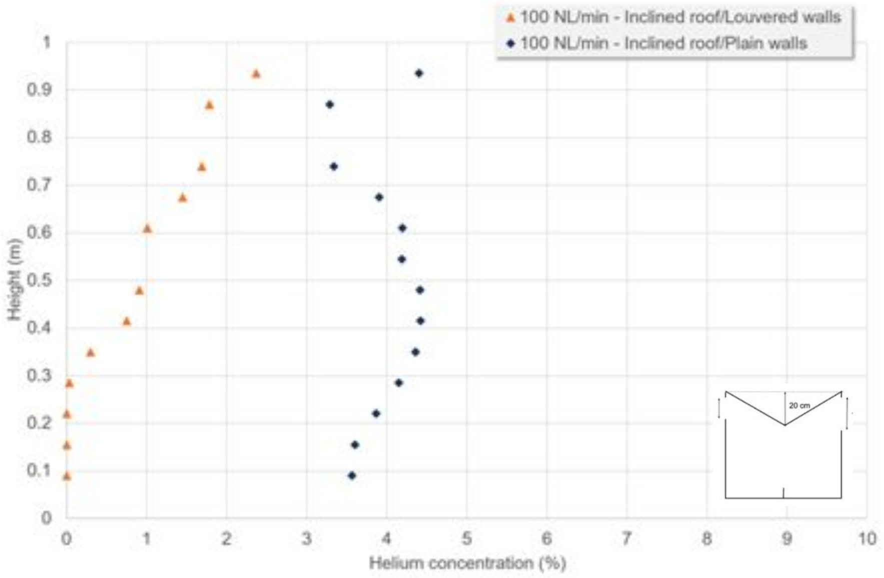
⇒ **Double inclination** of the roof fosters He build-up mitigation
**The more inclined** the roof is, the lower the maximum concentration in the enclosure is

# Processing container concept

## *Experimental measurements | Roof inclination & Louvered walls*

- **Design comparison** → Louvered vs Plain walls & Flat vs Inclined roof for 100 NL.min$^{-1}$




⇒ **Louvered walls mitigate accumulation inside the container**
**With louvered walls, positive impact of roof inclination on accumulation limitation is significantly reduced (± 2.5%)**
**Benefits of inclined roof are higher when walls are plain (4.5% vs 8.5%-He)**

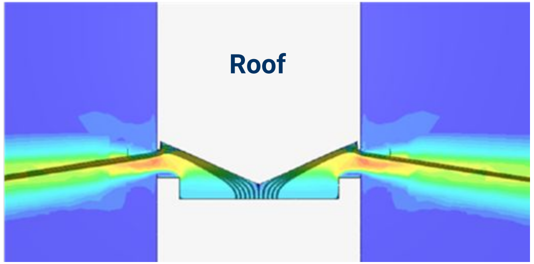
# Processing container

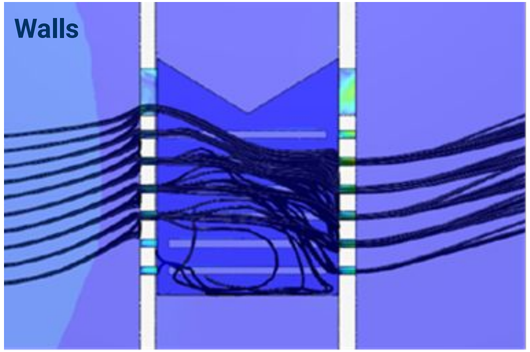
## *Visualization of ventilation fluxes & Distribution*

- Down scaled mock-up with Archimedes number approach
- Smokes with the 1-$m^3$ enclosure

⇒ Inlet fluxes by vertical louvers
Outlet fluxes by the roof

- Numerical simulation with SimScale



# Conclusions

# Conclusions

- **A novel design concept was proposed by students from the University of Delaware for the hydrogen refueling stations by modifying physical structure**
  - A **fruitful cross-disciplinary experience**

- **Analytical, experimental and numerical approaches were combined in order to evaluate hydrogen concentration and distribution**
  - **Significant positive effects on accumulation limitation in confined spaces - thanks to the specific studied designs - were demonstrated, with good agreement and complementarity between the investigated approaches**

- **For the experimental part**
  - Helium was used as a surrogate of hydrogen in order to work safely
  - Near real-scale mock-ups were constructed for the dispenser study
  - Down-scaled mock-ups for the processing container

- **This work highlighted that analytical calculations using Linden approach - in most cases - overpredict the helium concentration compared to the results obtained experimentally**

- **Numerical simulation was investigated for dispenser and container topics**
  - Numerical simulations seem to match with experimental observations
  - However, at this stage, the preliminary results obtained are more qualitative than quantitative
  - Further work is required in order to be able to extrapolate the experimental results for other sizes and designs
  - Warning should be made about the use of CFD via tools available online; numerical simulations require expertise

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# Thank You

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