# *The risk and reliability of hydrogen as a sustainable energy source*

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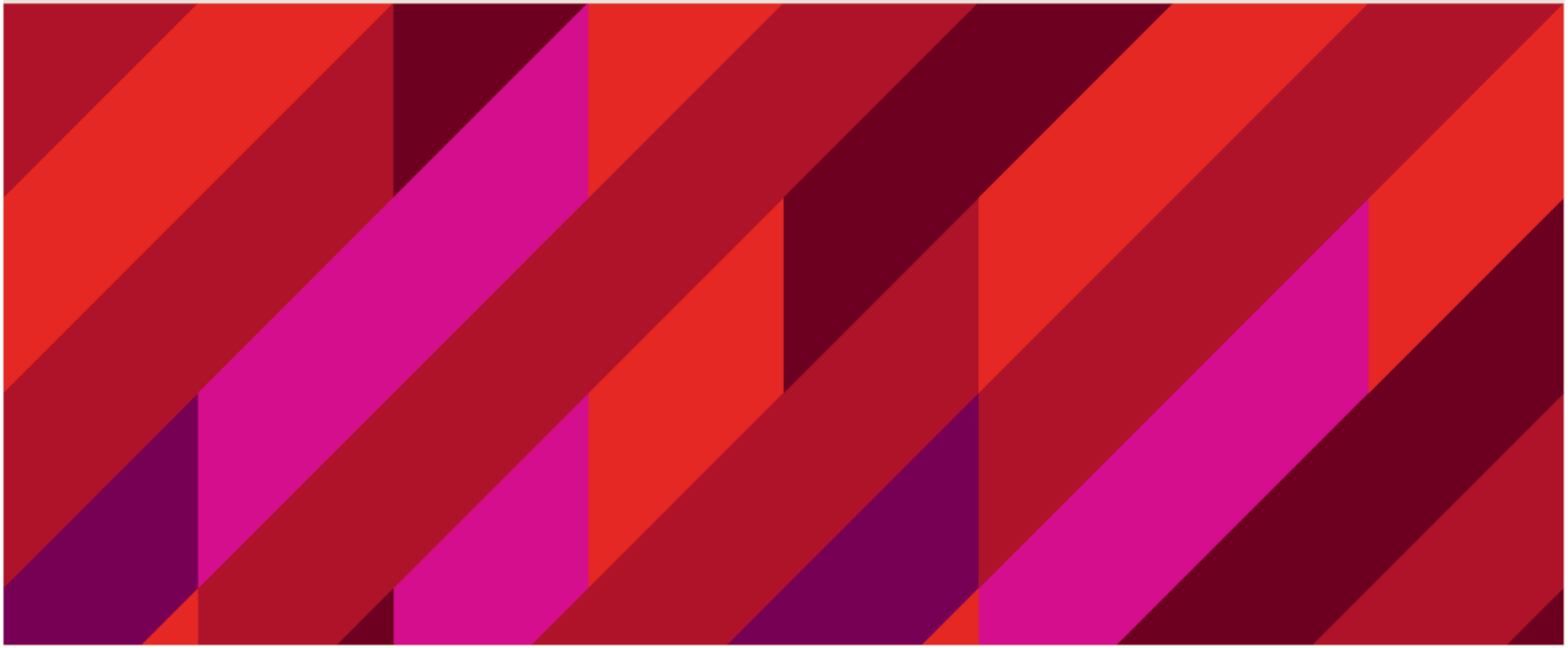

# Outlines

- ✓ Introduction
- ✓ Risk and Reliability in Engineering Operations
- ✓ Hydrogen safety
- ✓ Cases studied

# Sustainable Energy Research Centre

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## Photovoltaics and Solar Energy

**Director, Shujuan Huang**

- development of photovoltaic materials for next generation high efficiency solar cells
- development of device fabrication technologies to reduce the cost of power generation

## Hydrogen

**Director, Fatemeh Salehi**

*Production and Utilisation*

- bio-hydrogen production to increase the rate and yield of hydrogen production with minimal by-products
- Chemical production of hydrogen using a sustainable chemical looping process

*Application and Safety*

- provide scientific and technical knowledge in understanding the safety aspects related to hydrogen energy applications
- risk analysis and consequence modelling regarding hydrogen applications

## Grid integration

**Director, Sara Deilami**

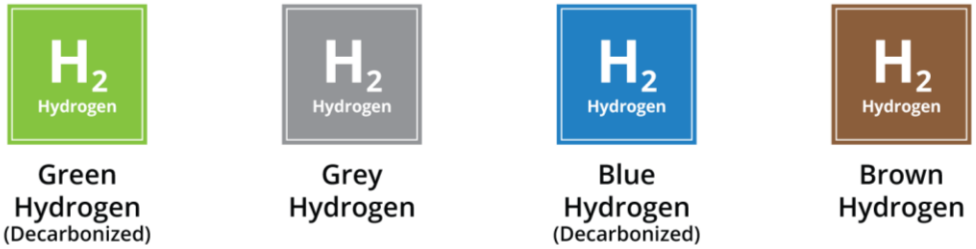
- energy management and distribution for commercial and residential systems, micro grid and grid integration
- integration of electrical vehicles into the grid for charging and supply

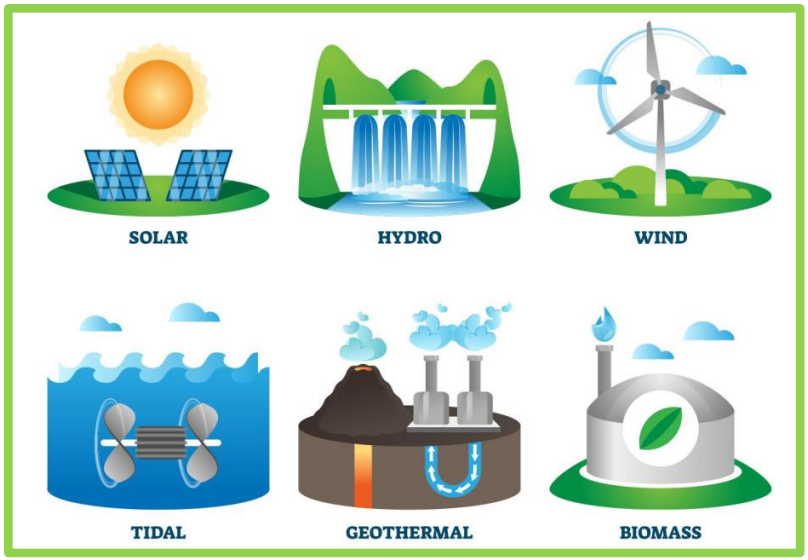
## Energy Economics

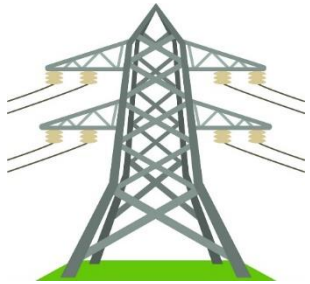
**Director, Stefan Trueck**

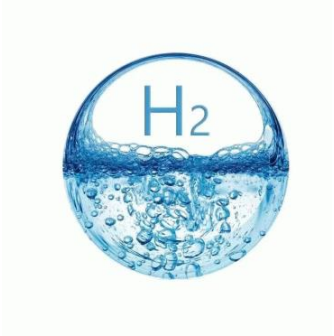
- Financial innovation strategies to stabilise energy markets transitioning from fossil-fuel fired power generation to a renewable energy model

# Introduction






**Hydrogen characteristics**

- High energy density
- Storage options
- Environmentally friendly
- Non-toxic
- Availability

# Introduction

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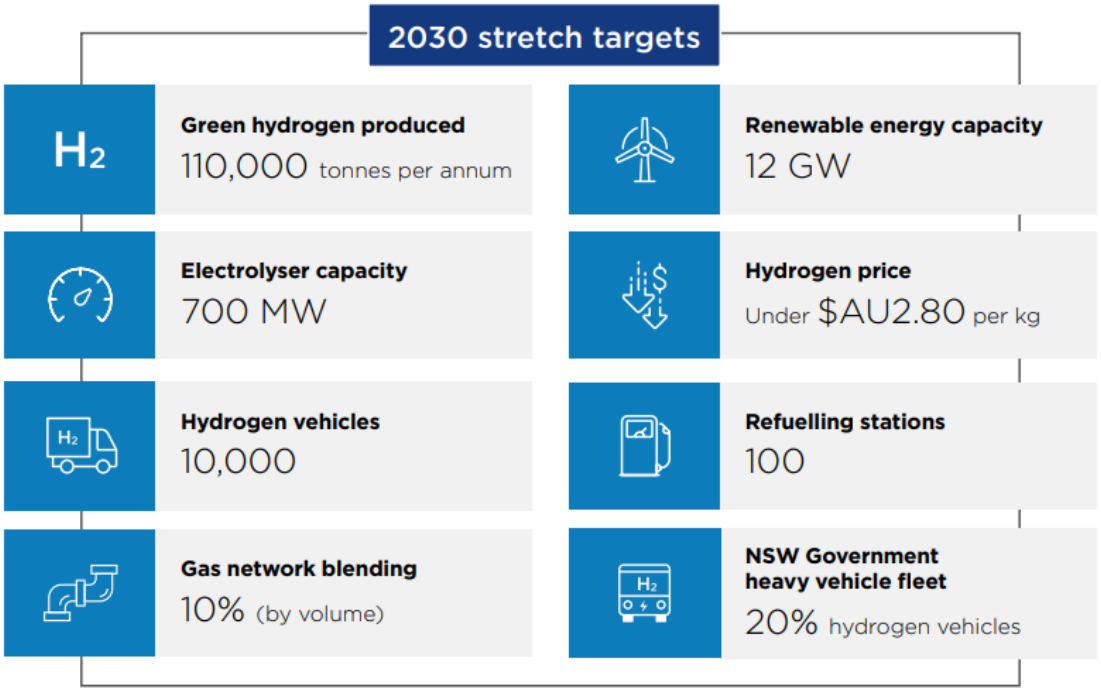
International Partnership for Hydrogen and Fuel Cells in the Economy

# Introduction

- The Council of Australian Governments (COAG) Energy Council
- National Hydrogen Strategy Taskforce




# Risk Assessment

**Risk**

Assessment of the presence and impact of unwanted situation at time t

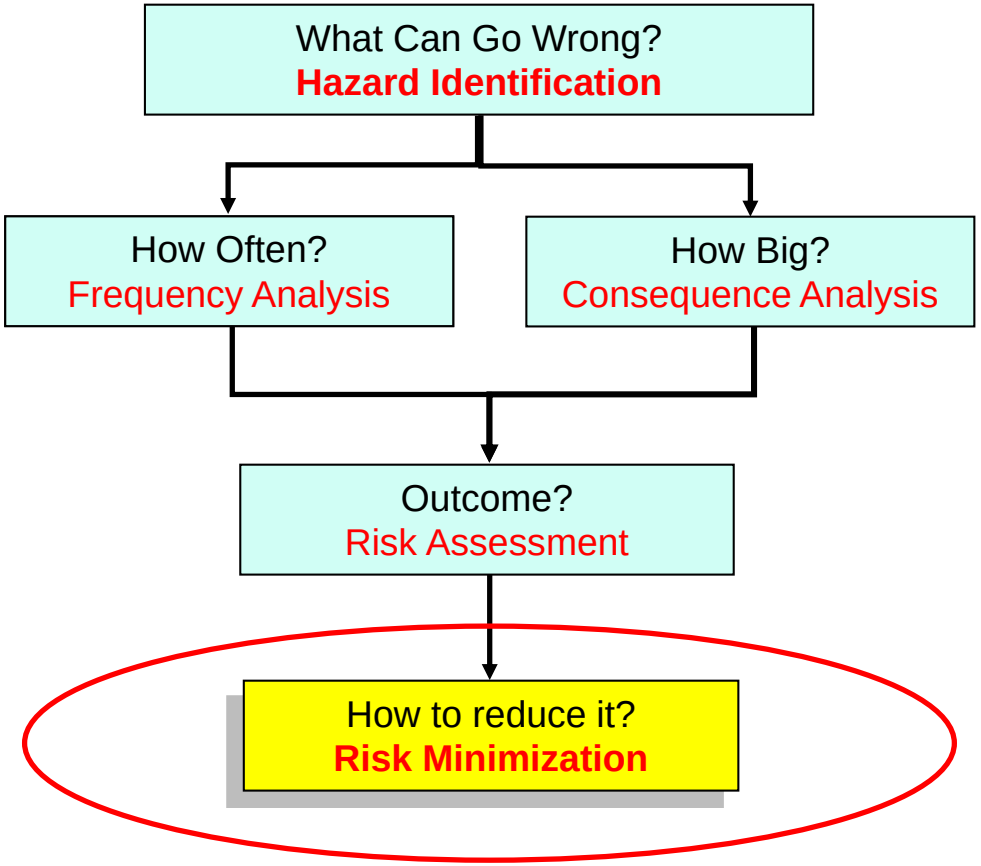
Risk (t) = occurrence of unwanted situations & its impact

$$Risk(t) = F(t).Loss\ (t)$$

**Safety**

Absence of unwanted situation in system/operation at time t

$$S(t)\ \alpha\ \frac{1}{Risk\ (t)}$$




**Reduce Risk**

- Reduce likelihood (probability)
- Reduce impact

# Scope of Our Research

## Risk, Safety and Reliability Engineering

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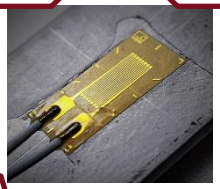
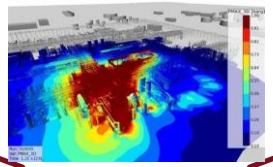
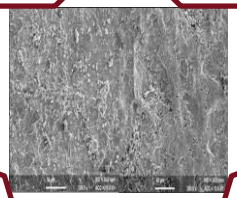


Materials Failure Analysis

Accident Likelihood Assessment

Consequence Modleing

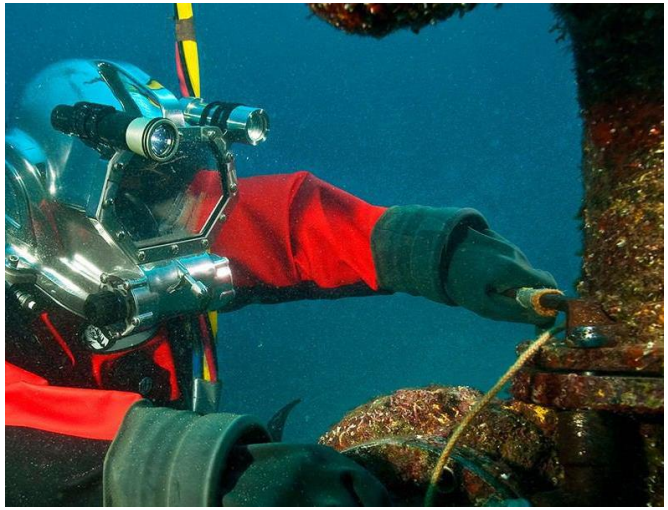


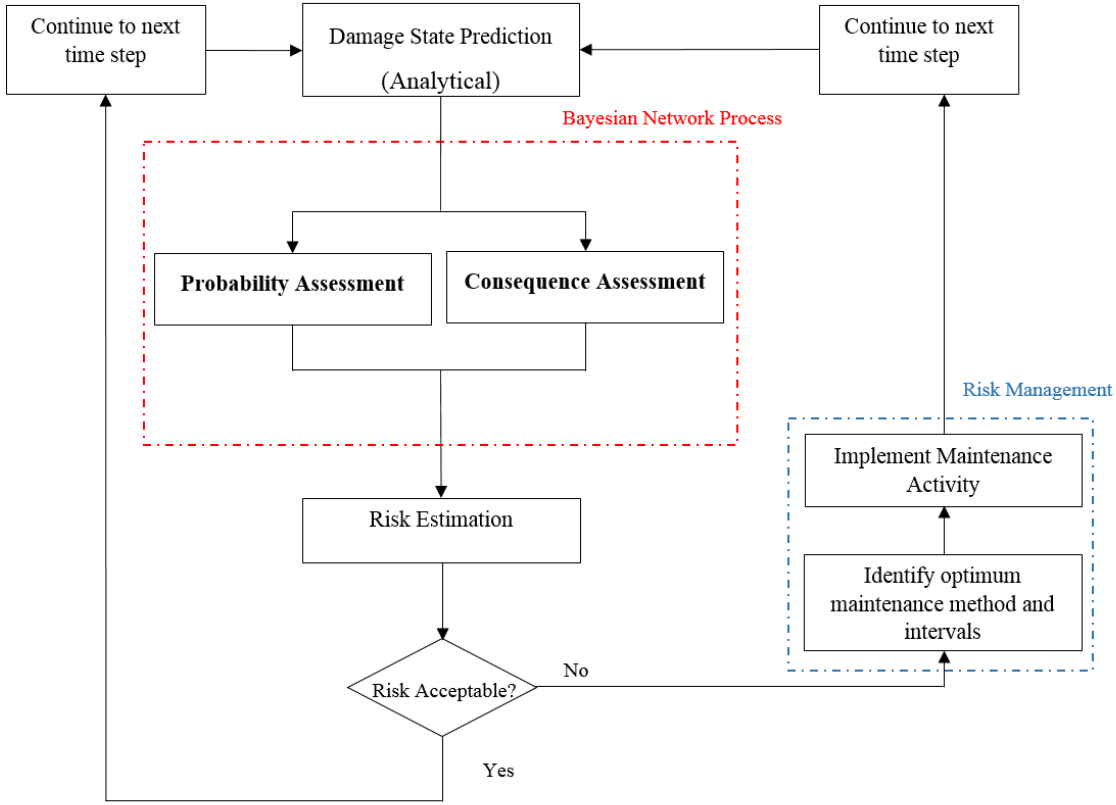
Hydrogen dispersion Chamber at Macquarie University

# Inspection & Maintenance Planning

Optimization of **repair/service schedule** with an aim to **minimize cost** and **maximize safety & availability**

# Risk-Based Maintenance





# Dynamic Fatigue Crack Modeling

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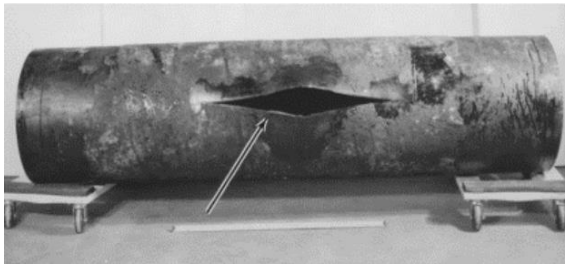
$$\frac{da}{dN} = C(\Delta K)^m$$ Paris' law for fatigue damage

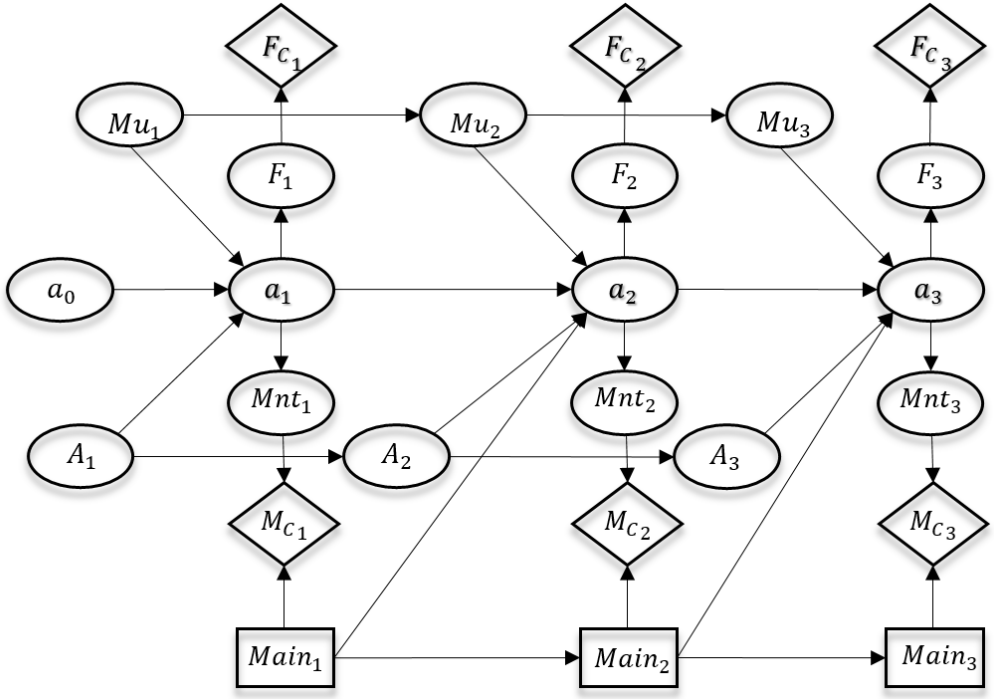
$$a_i = \left(a_{i-1}^{\frac{2-m}{2}} + M_U K A^m\right)^{\frac{2}{2-m}}, m \neq 2$$



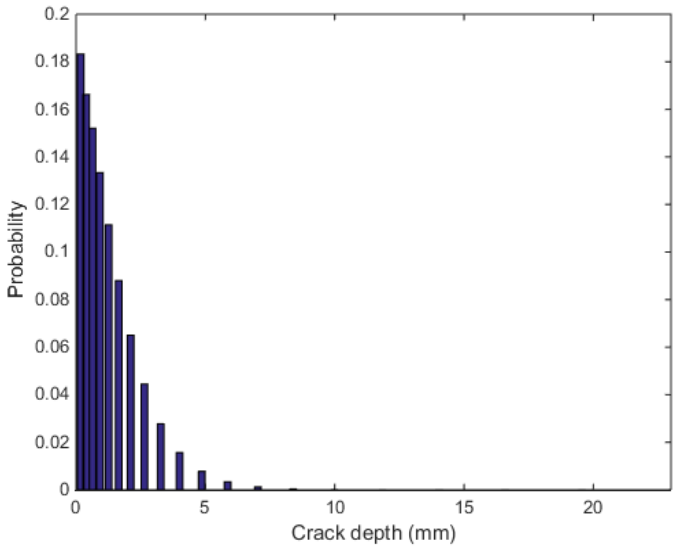
$$Limit\ State$$

$$F_i = a_c - a_i \quad \begin{cases} F_i > 0 & safe \\ F_i \leq 0 & fail \end{cases}$$

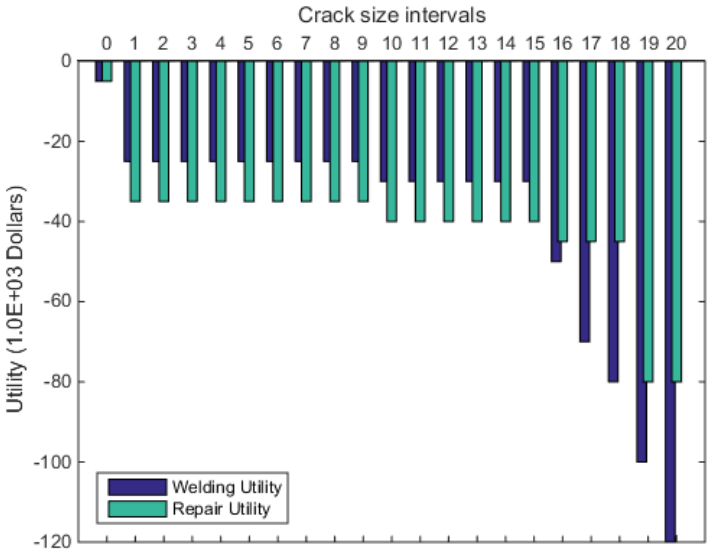
| Variable | Description |
|---|---|
| $a_0$ | Initial crack depth |
| $a_i$ | Actual crack depth |
| N | Load cycles |
| ΔK | Stress intensity factor |
| C, m | Material parameters |
| $F_i$ | Failure Function |
| A | Weibull scale parameter |
| $M_U$ | Model uncertainty |
| Mnt | Crack detection |
| $M_C$ | Maintenance cost |
| $F_C$ | Failure cost |



# Crack Size and Cost



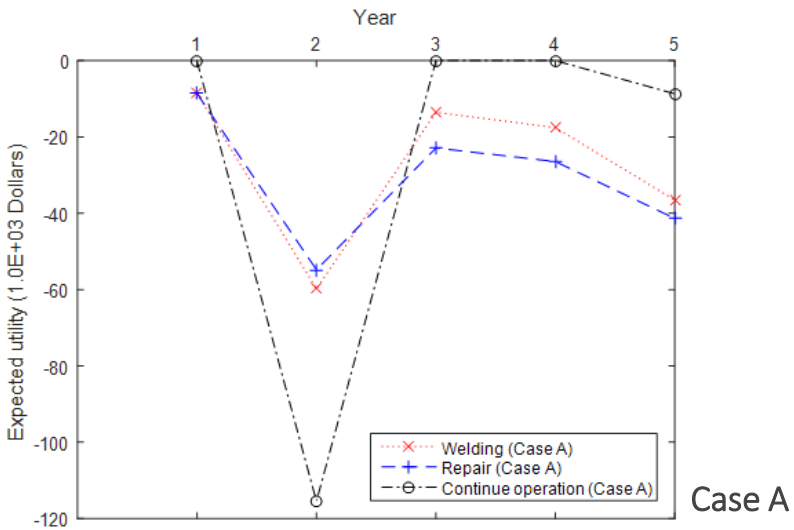

Initial crack size distribution ($a_0$)



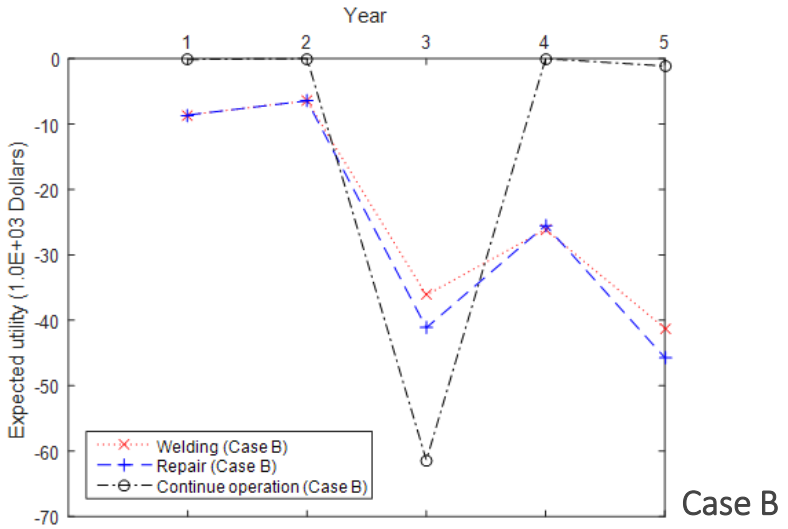

Utility functions of decision alternatives

| Year | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Case A | No Detection | State 15 | - | - | - |
| Case B | No Detection | No Detection | State 11 | - | - |
| Case C | State 8 | State 12 | State 14 | - | - |

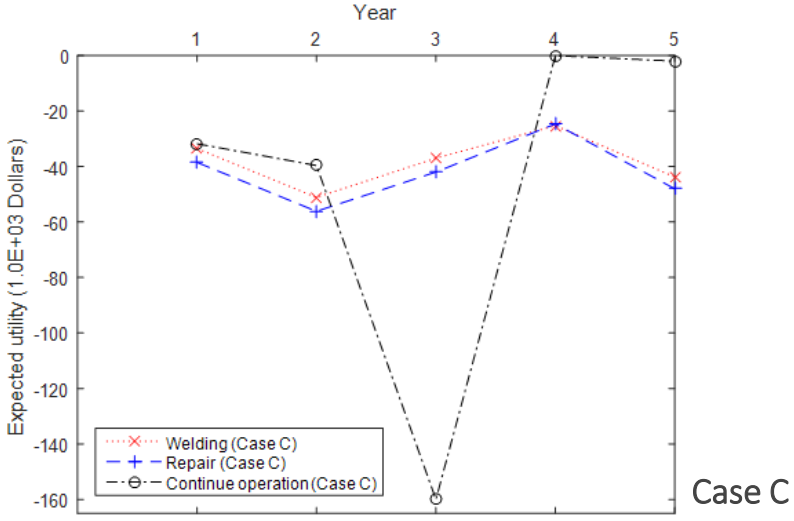
# Comparison Results




Case A




Case B




Case C

| Year | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Case A | No Det. | State 15 | - | - | - |
| Case B | No Det. | No Det. | State 11 | - | - |
| Case C | State 8 | State 12 | State 14 | - | - |

# Hydrogen accidents

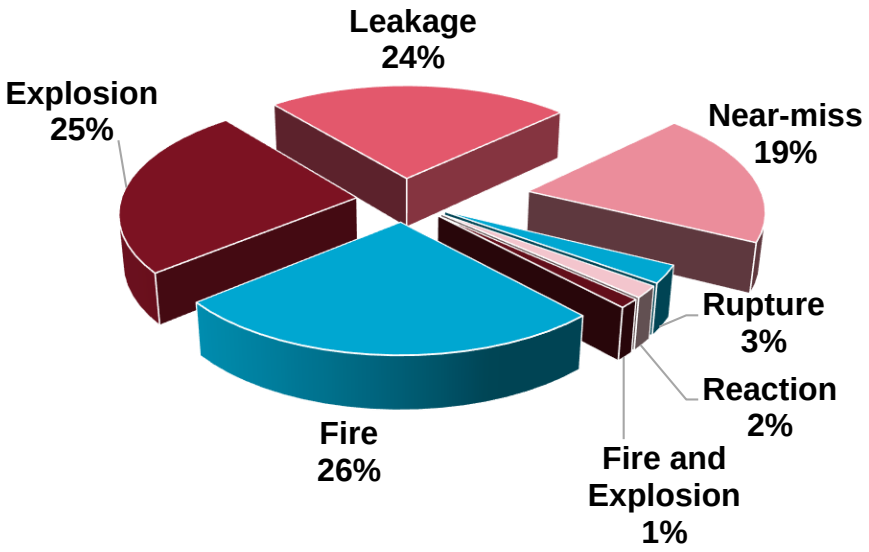
230 accidents over the last two decades: (H2Tool database)

**Major causes**

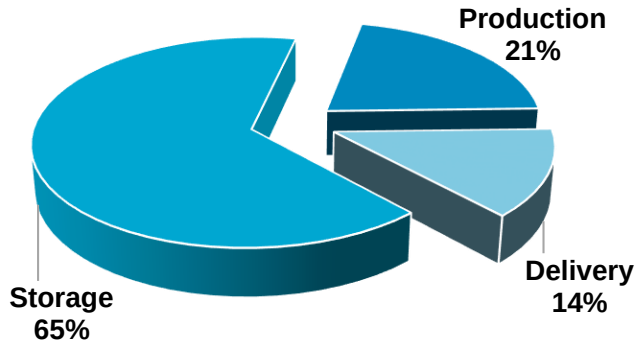
- Human errors
- Equipment failures
- Design issues

**Consequences**

- Property damage
- Injury to human
- Loss of human life

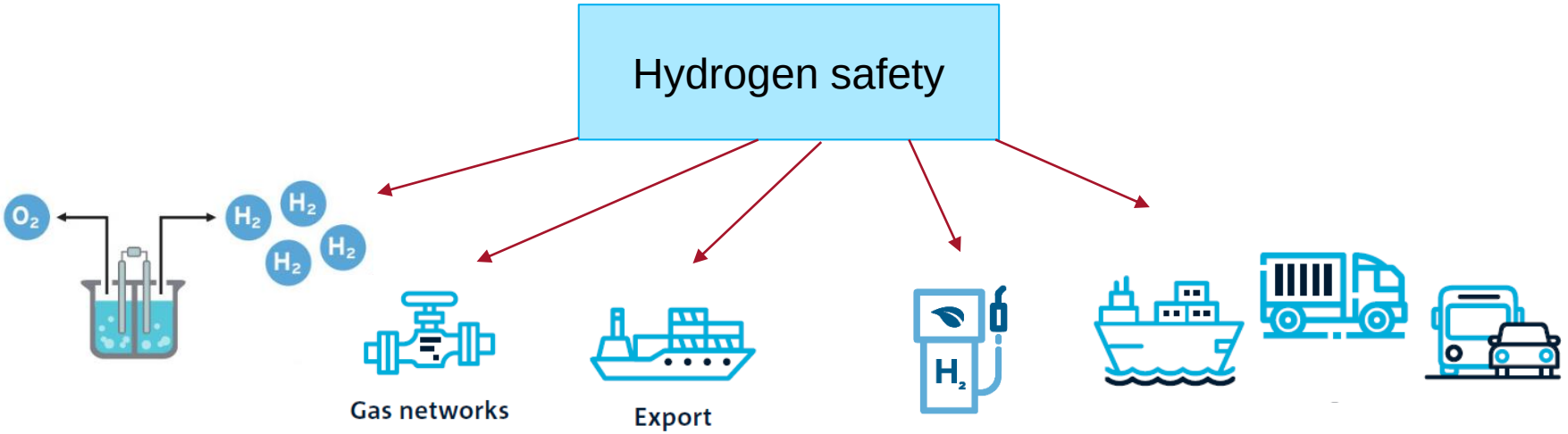



Accident




Facility

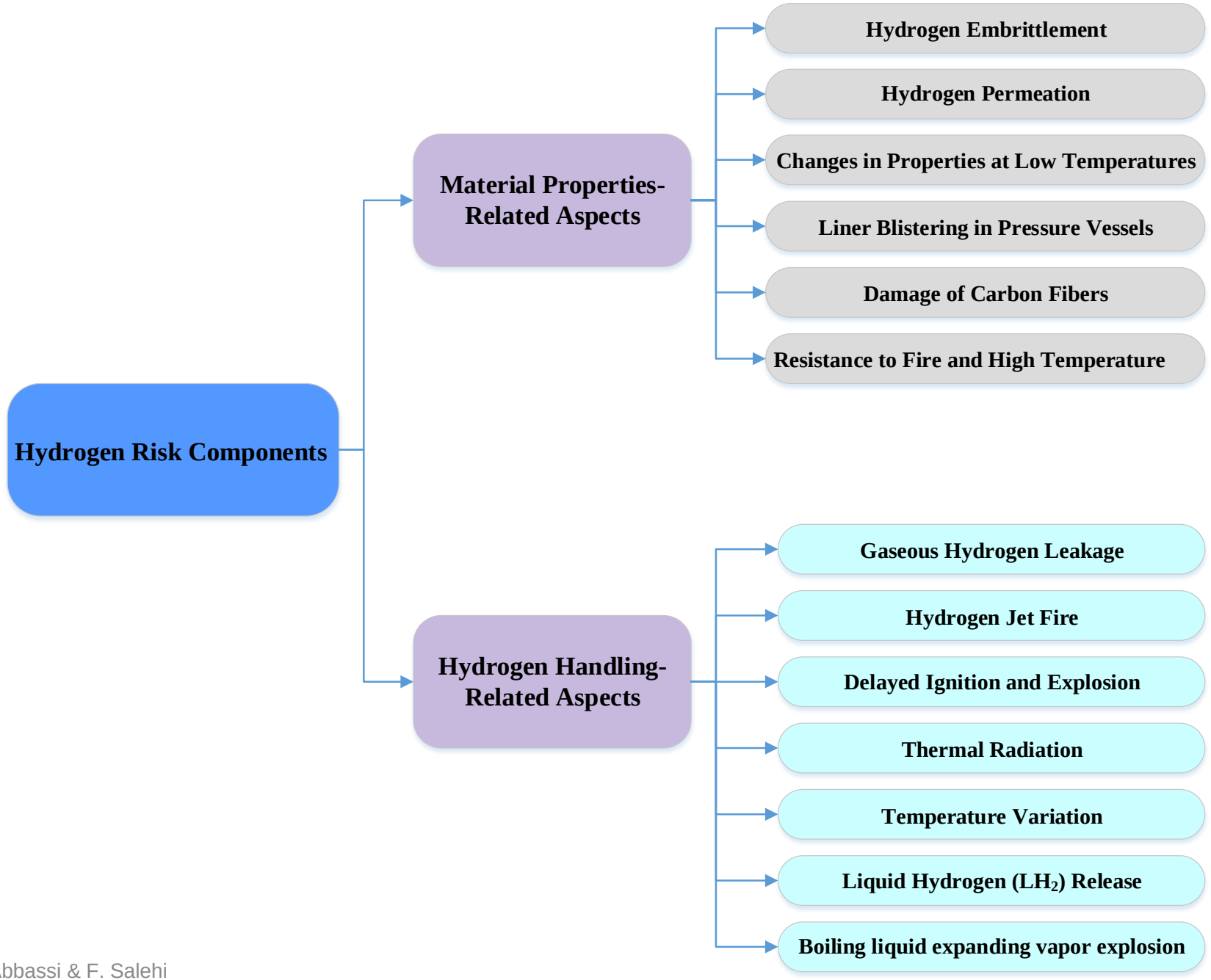
# Hydrogen safety





Liquid Hydrogen


Gaseous Hydrogen


Hydrogen Risk Components
Material Properties-Related Aspects
Hydrogen Embrittlement
Hydrogen Permeation
Changes in Properties at Low Temperatures
Liner Blistering in Pressure Vessels
Damage of Carbon Fibers
Resistance to Fire and High Temperature
Hydrogen Handling-Related Aspects
Gaseous Hydrogen Leakage
Hydrogen Jet Fire
Delayed Ignition and Explosion
Thermal Radiation
Temperature Variation
Liquid Hydrogen ($LH_2$) Release
Boiling liquid expanding vapor explosion

# Hydrogen Safety: Challenges with Current Modeling

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- ✓ Safety of hydrogen infrastructures are vital in the growth of hydrogen economy
- ✓ Several risk models have been developed to assess the safety of hydrogen infrastructures, however, most of them have the shortcomings of:
  - Being static in nature, not properly observing the variability occurring in operation via time
  - Lack of enough precise data of young emerging technologies like hydrogen which leads to uncertainty in input and output parameters
  - Lack of considering the dependencies among the root failures of complex systems
  - Attending to mechanical failures without paying enough attention to human and organizational failures

# Hydrogen safety – production site

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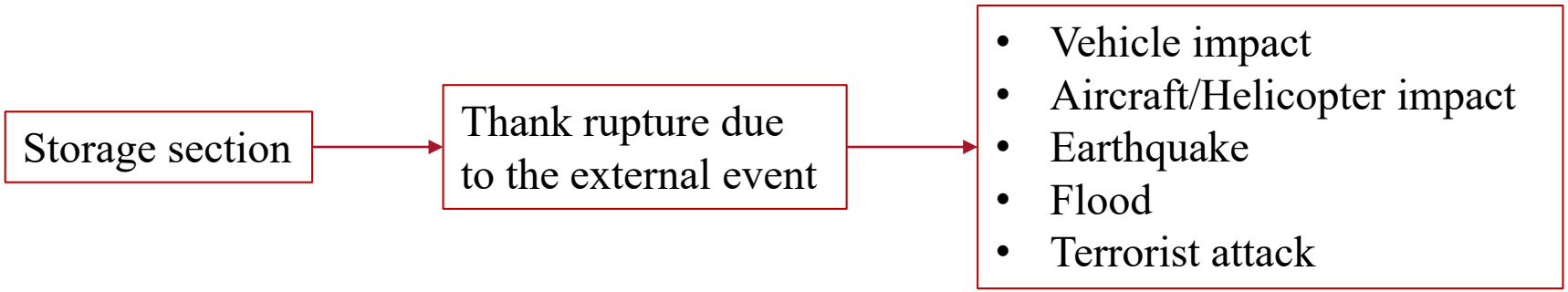
**Failures considered in:**

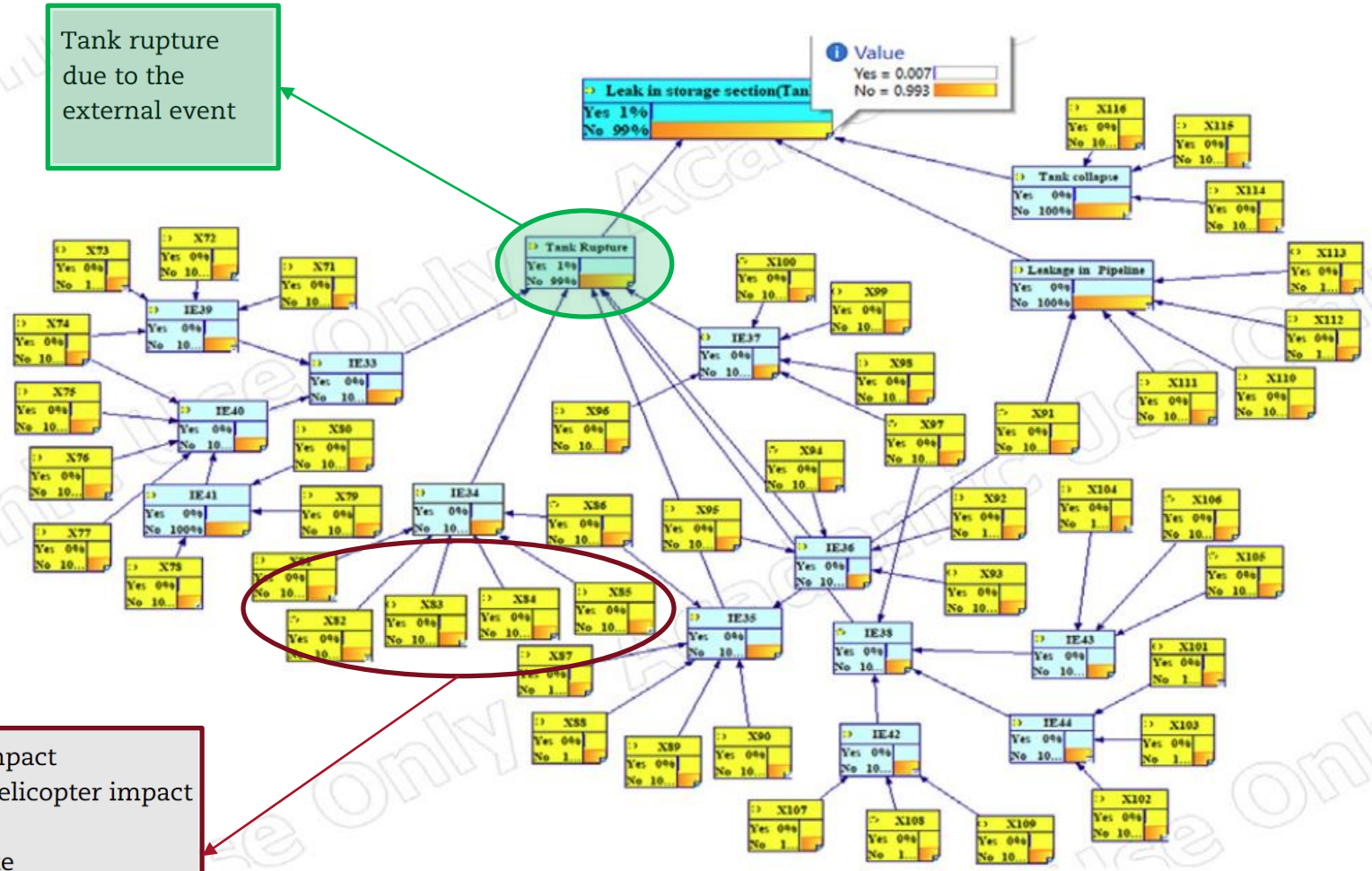
- Chemical section
- Mechanical section
- Storage section

**Cause-effect model of the hydrogen release accident scenario**

- Failure and causes:
  - ✓ Identify all possible failures of the main equipment, leading to a hydrogen leak,
  - ✓ How failures are connected and how they can logically lead to the accident scenario
- Likelihood values for each cause
  - Background history
  - Expert judgment (use conventional methods)



# Hydrogen safety – production site



# Hydrogen safety - Production site

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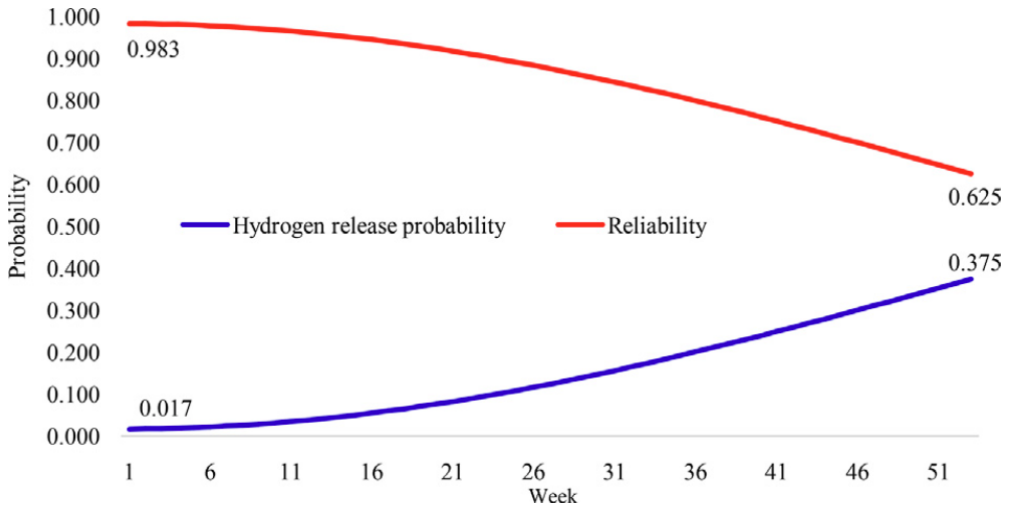
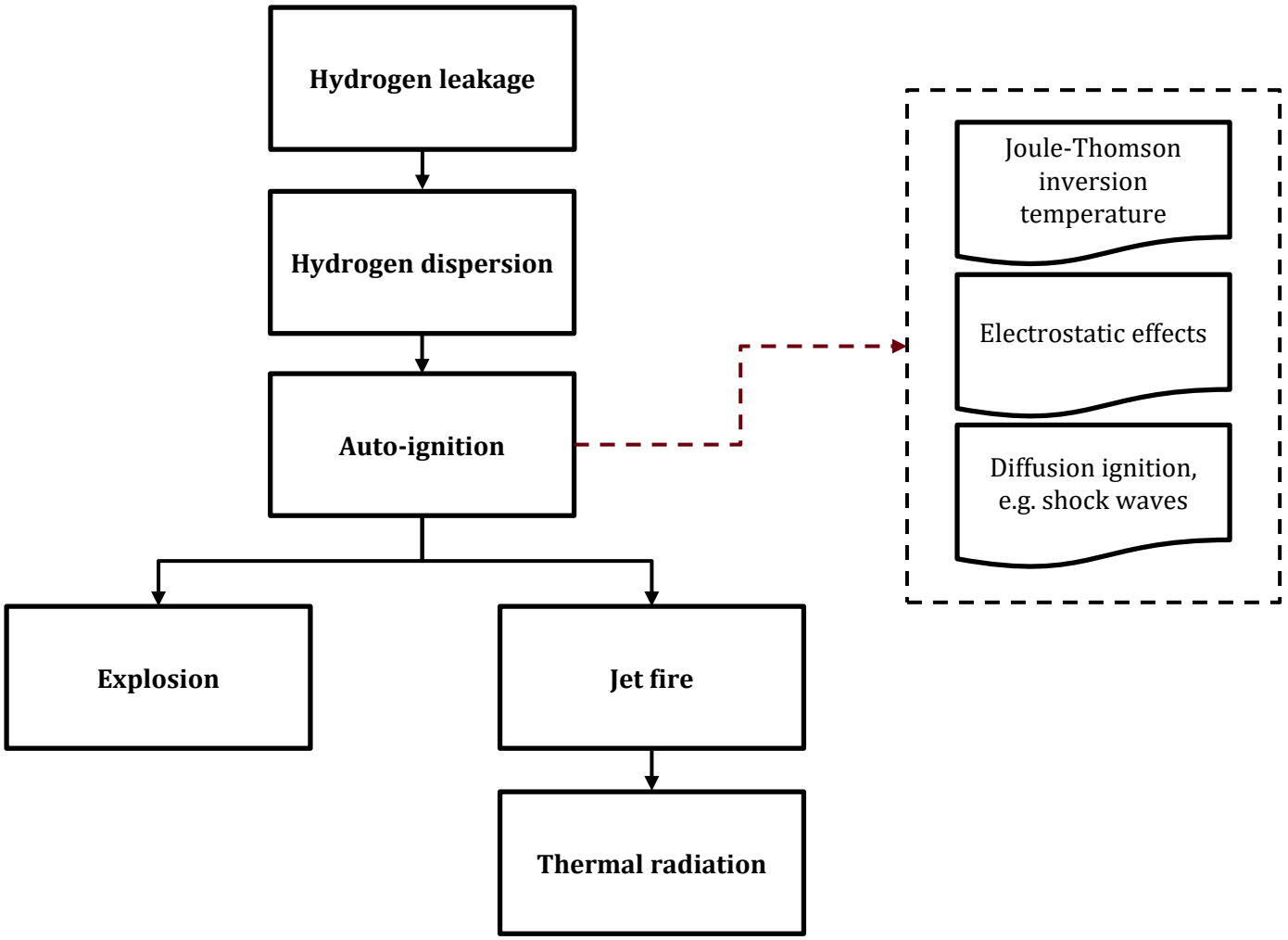
- ✓ A significant change in the system reliability within a year confirms the system degrades dramatically during the considered time interval




- ✓ Dynamic modelling of hydrogen release probability and the system reliability

- Safety barriers
- Backward analysis: find critical cause of accident

# Hydrogen Accidents: Consequence Modelling



# Computational fluid dynamics

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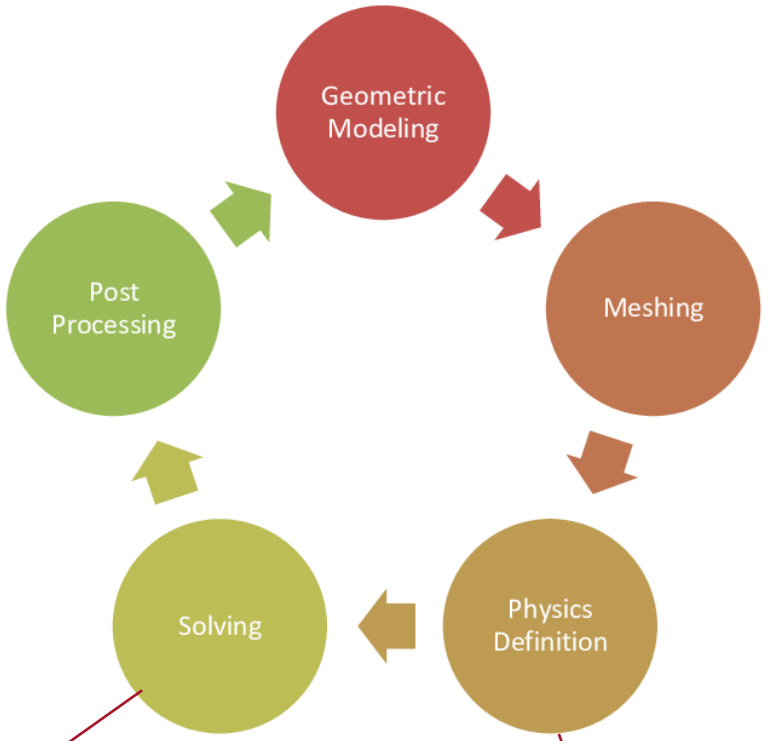
## Governing equations

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_i}}{\partial x_i} = 0$$

$$\frac{\partial \bar{\rho}\widetilde{u_i}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_i}\widetilde{u_j}}{\partial x_j} + \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \widetilde{\sigma_{ij}}}{\partial x_j} = -\frac{\partial \bar{\rho}\tau_{ij}^r}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\overline{\sigma_{ij}} - \widetilde{\sigma_{ij}}\right)$$

$$\frac{\partial E_f}{\partial t} + \bar{u}_j\frac{\partial E_f}{\partial x_j} + \frac{1}{\rho}\frac{\partial \bar{u}_i\bar{p}}{\partial x_i} + \frac{\partial \bar{u}_i\tau_{ij}^r}{\partial x_j} - 2\nu\frac{\partial \bar{u}_i\overline{S_{ij}}}{\partial x_j} = -\epsilon_f - \pi$$

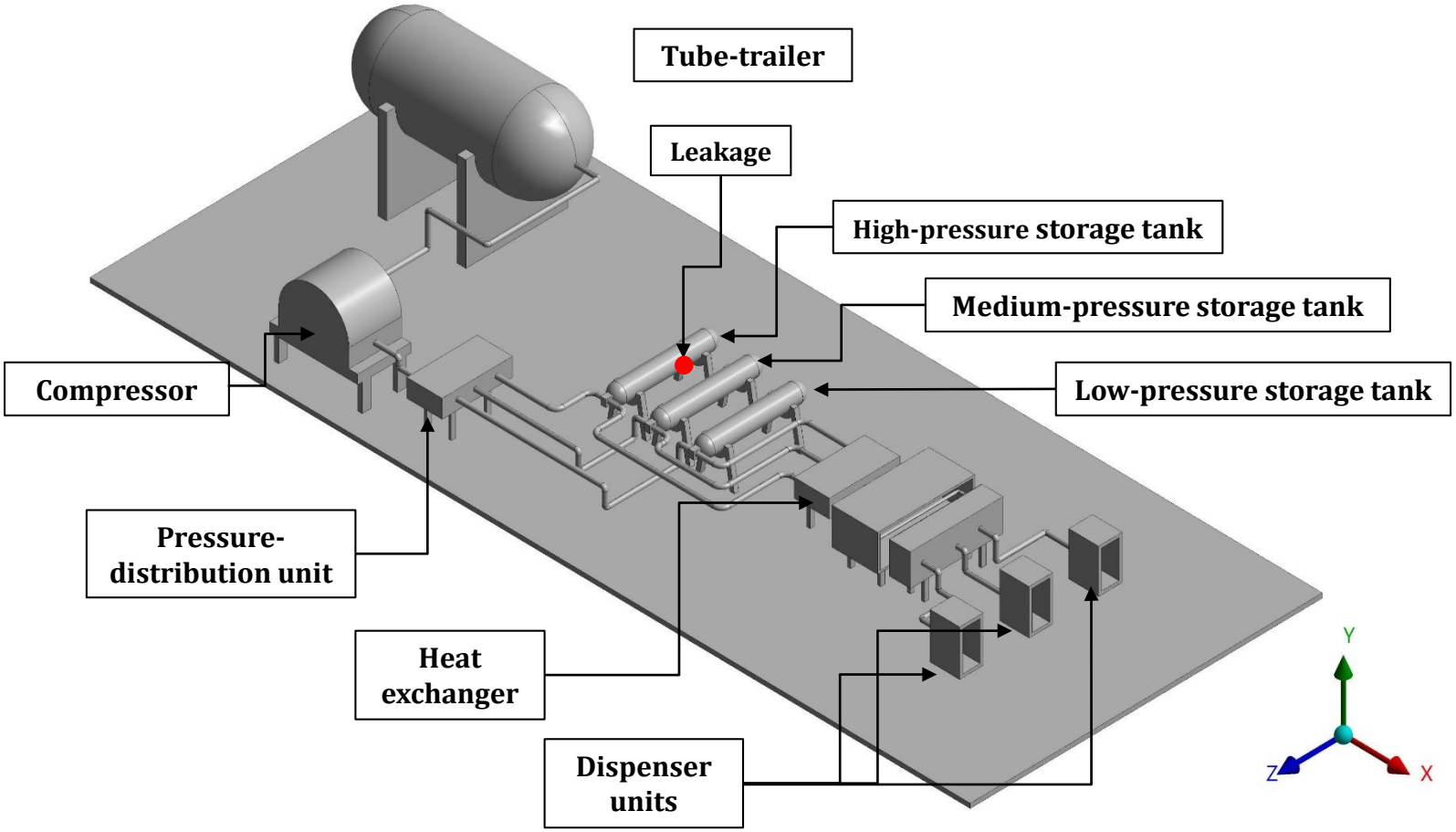
$$\frac{\partial \bar{\rho}\widetilde{Y_\alpha}}{\partial t} + \frac{\partial \bar{\rho}\widetilde{u_j}\widetilde{Y_\alpha}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}\left(\widetilde{u_jY_\alpha} - \widetilde{u_j}\widetilde{Y_\alpha}\right) - \bar{\rho}\bar{D}_\alpha\frac{\partial \widetilde{Y_\alpha}}{\partial x_j}\right) + \bar{\dot{\omega}}_\alpha$$



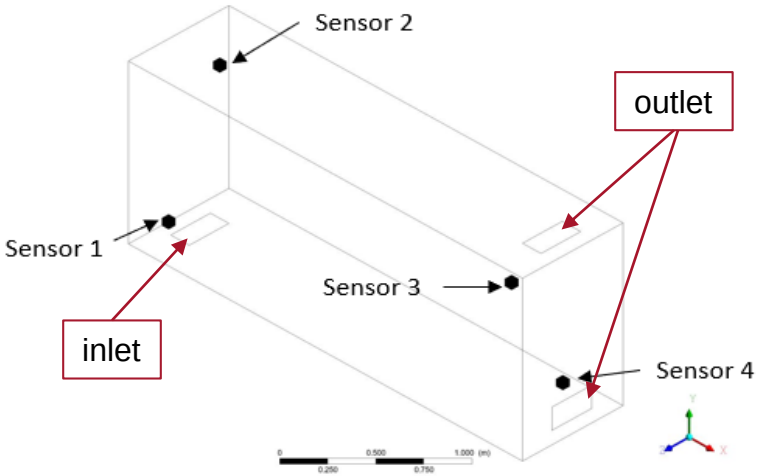

- Numerical schemes
- Time step
- Residuals
- Solvers

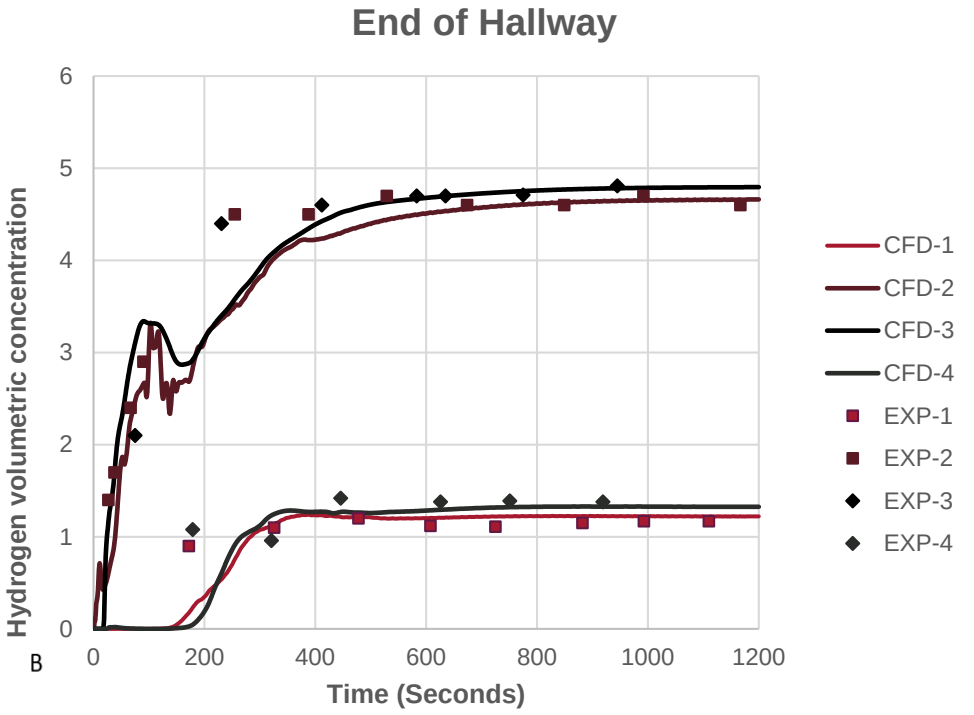
- Turbulence model
- Combustion model
- Chemistry model
- Heat transfer model

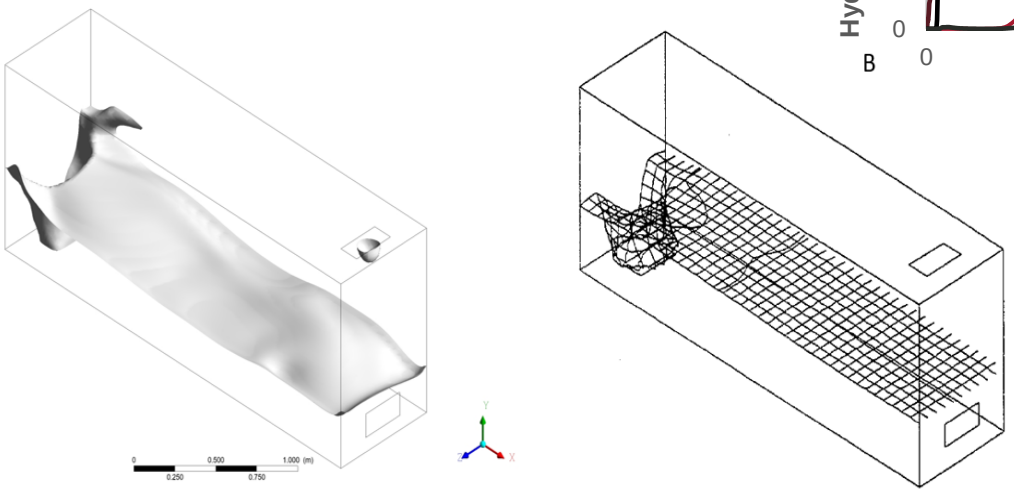
# Hydrogen refuelling station



# Hydrogen dispersion



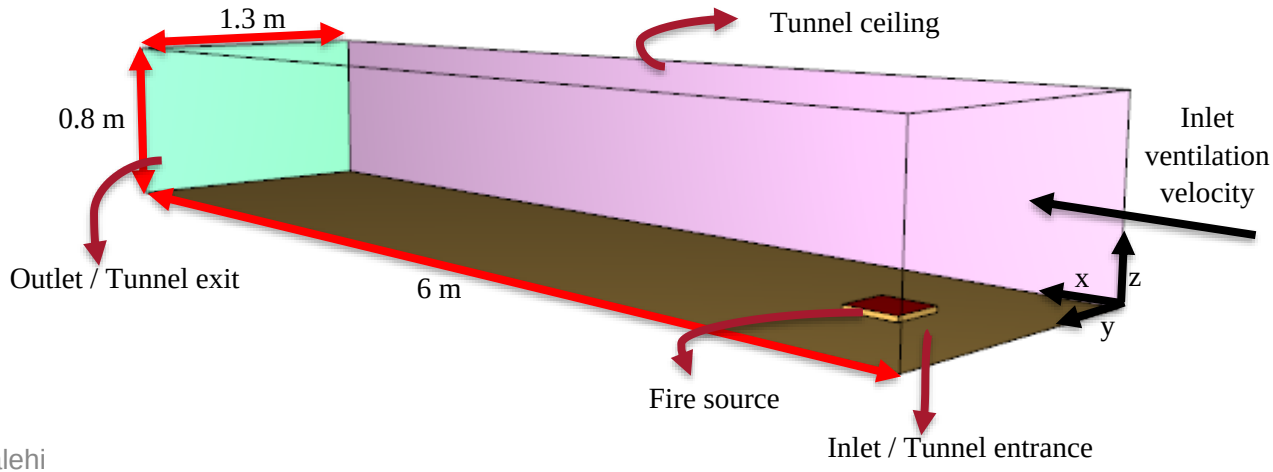
**Hydrogen concentration of 1%**

# Hydrogen fire

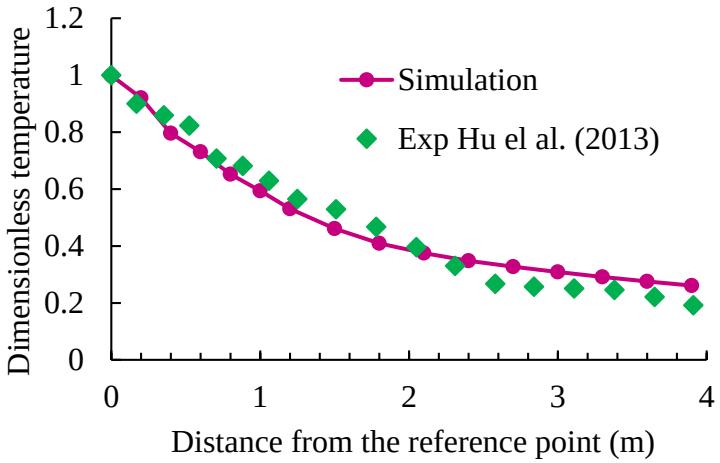
(Fuel Leak Simulation. Swan et al., 2001)

| Simulation set | Inlet ventilation velocity (m/s) | Fuel type | Slope (%) | Storage capacity (%) |
|---|---|---|---|---|
| I | 0, 1.2 | Hydrogen | 0 | 100 |
| | 0, 1.2 | Propane | | |
| II | 0, 0.6, 1.2 | Hydrogen | 0, 3, 6, 9 | 100 |

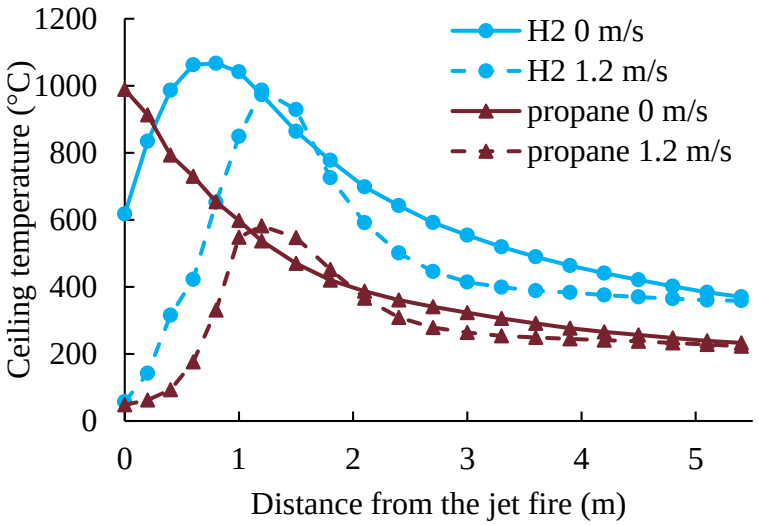
| Fuel type | Burner Size | HRRPUA | $\Delta H_c$ | HRR |
|---|---|---|---|---|
| Hydrogen | 0.09 $m^2$ | 8,900 $kW/m^2$ | 119.7 MJ/kg | 801 kW |
| Propane | | 4,564 $kW/m^2$ | 45.8 MJ/kg | 410 kW |

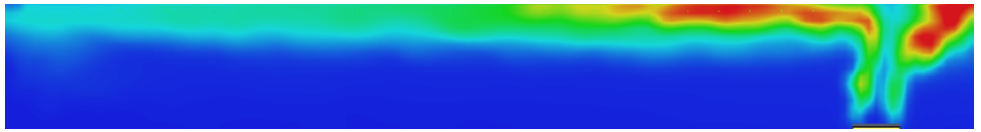


# Hydrogen versus propane fire

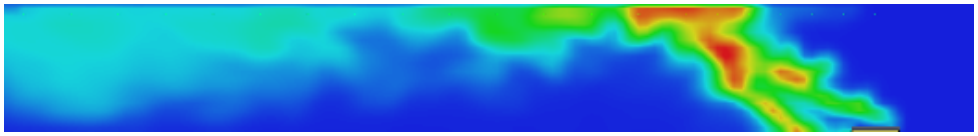



$$\frac{\Delta T_x}{\Delta T_0} = \frac{T_x - T_a}{T_0 - T_a}$$



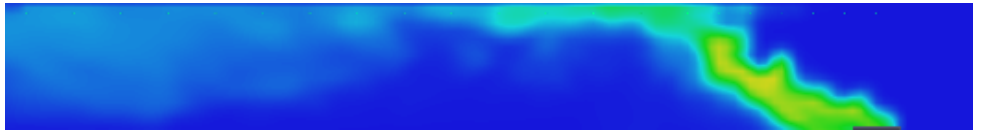



Hydrogen 0 m/s



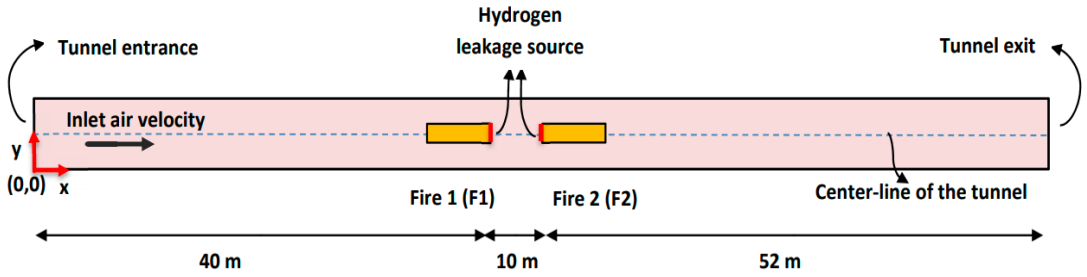
Hydrogen 1.2 m/s

Propane 0 m/s

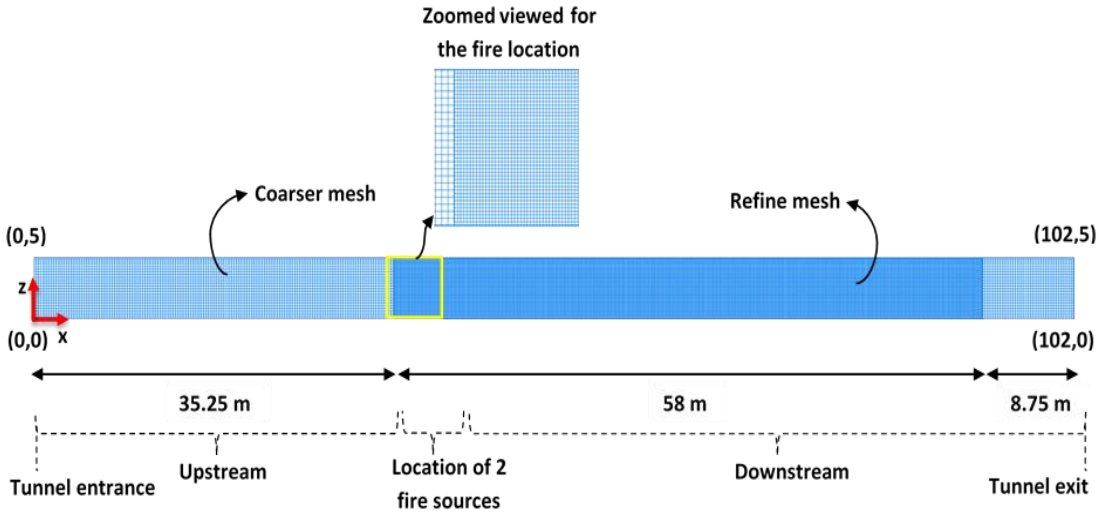


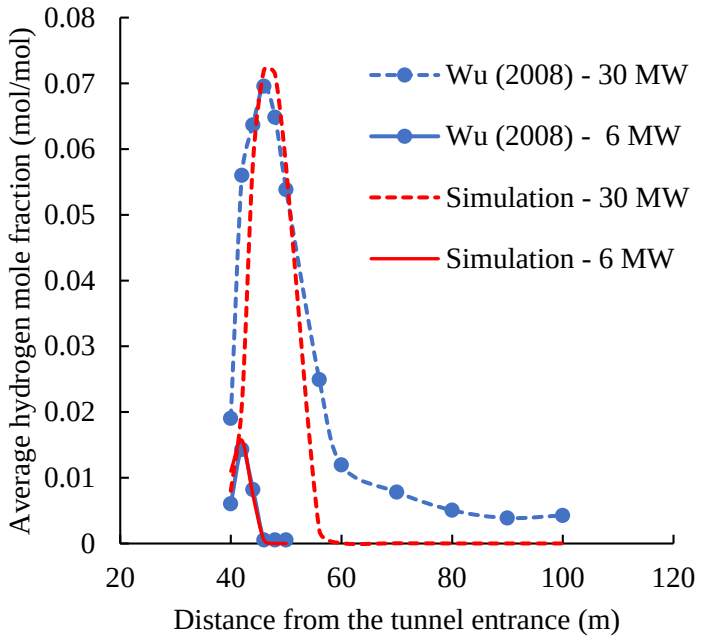
Propane 1.2 m/s

# Multiple hydrogen fire

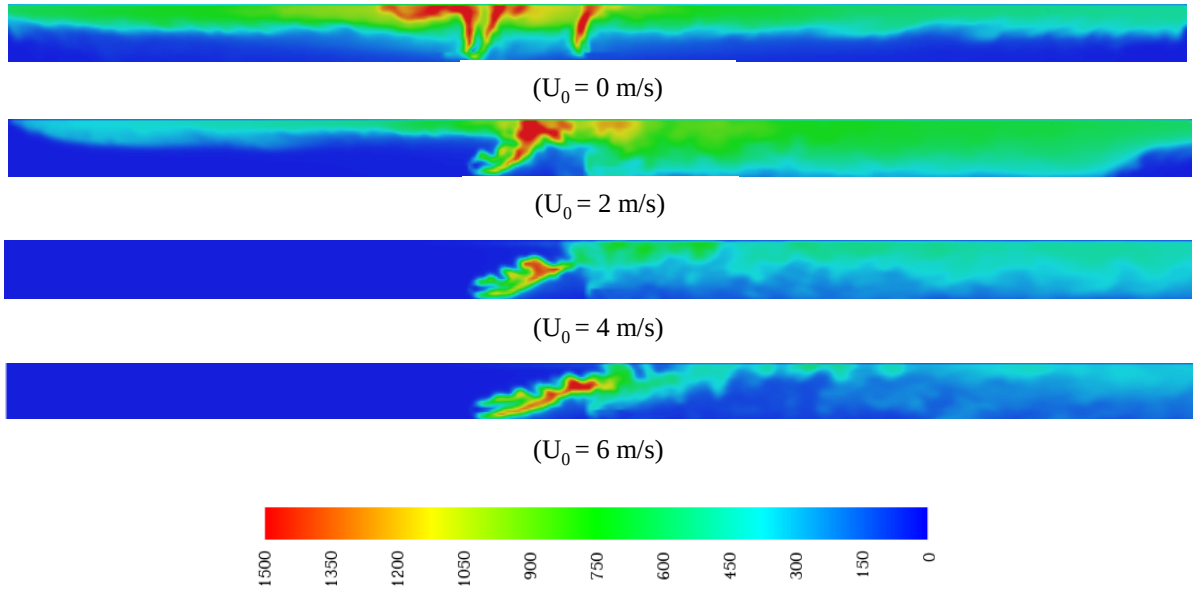



| F1 HRR (MW) | F2 HRR (MW) | Slope (%) | Velocity (m/s) |
|---|---|---|---|
| 5 | 40 | 0-5 | 0-7 |



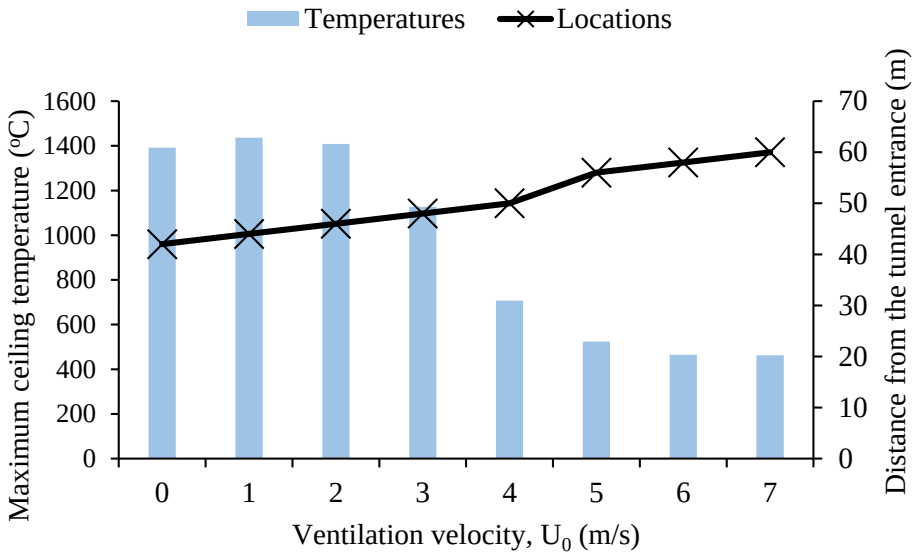
# Multiple hydrogen fire



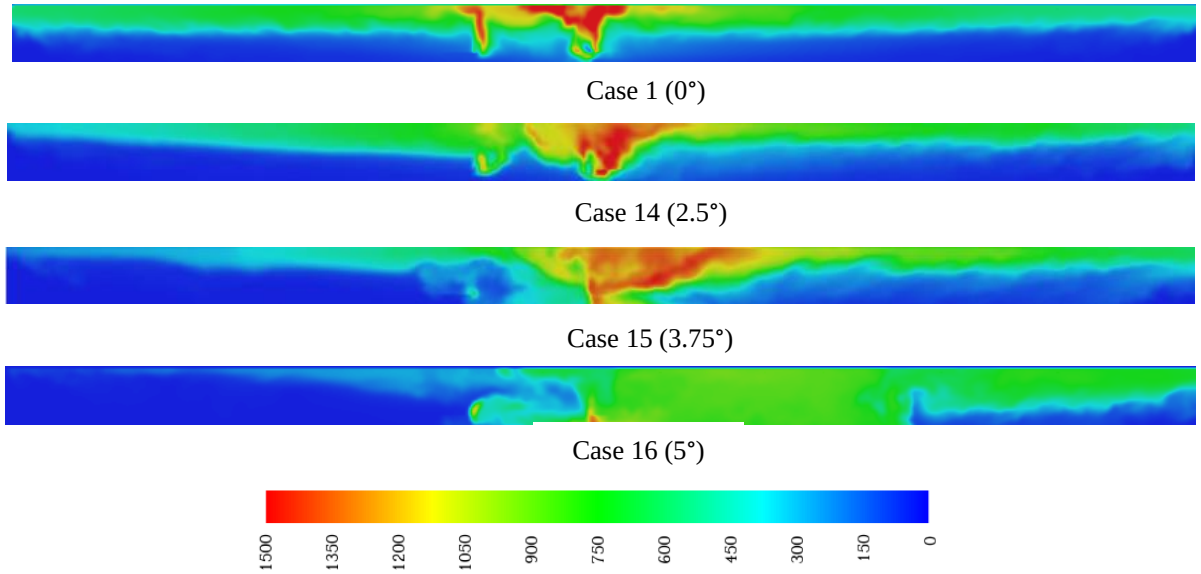

Ventilation velocity

- Air quality in the tunnel.
- Impacts of heat and smoke
- The egress of tunnel users
- Support firefighting

- Enhance the dispersion rate of hydrogen away from the combustion zone:
  lowering of the combustion rate
- Better mixing of the hot vaporized fuel particles and oxygen:
  enhance combustion rate



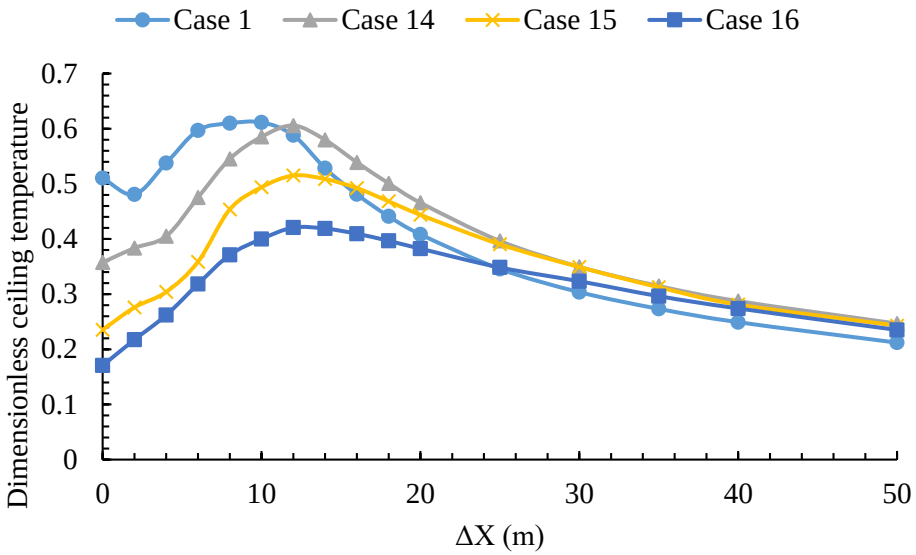
# Multiple hydrogen fire



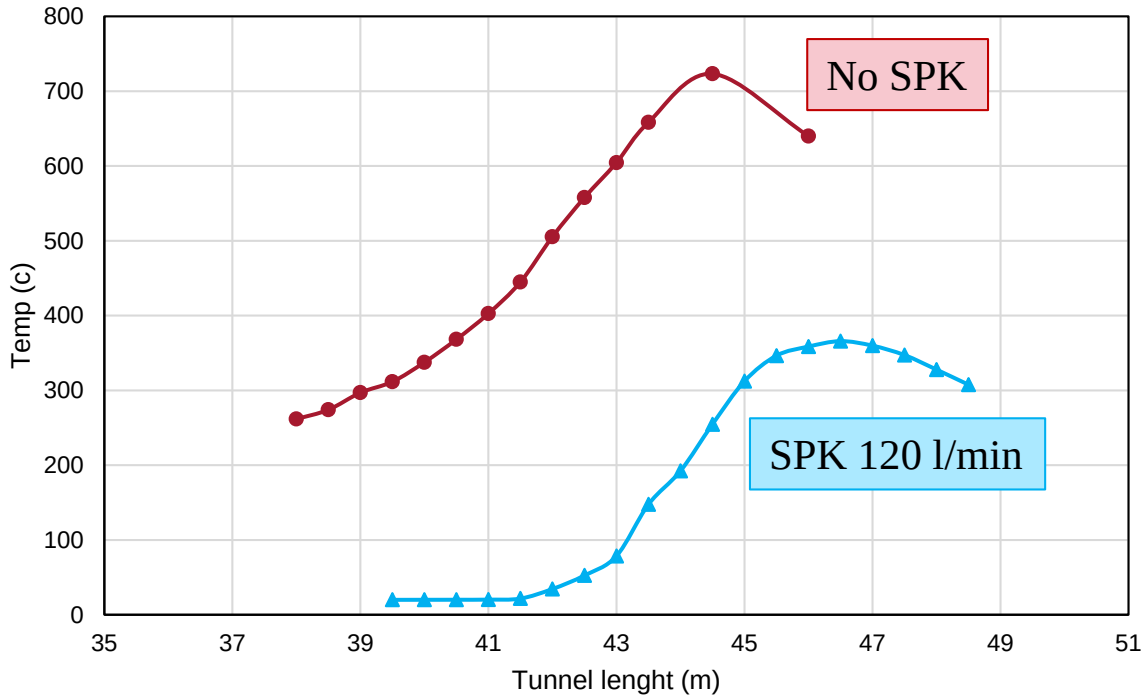

Tunnel slope

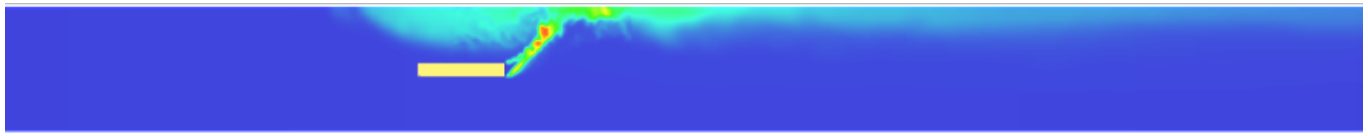
- 50 km/h: slope<5%
- 30 km/h: slope<8-9%

- Increasing the slopping clears the upstream from the hot gas, while spreading and covering them downstream
- The tilting of the flames in the direction of the slope: the shift of the peak ceiling temperature
- The rapid dispersion of the leaked hydrogen reduced the ceiling temperatures



# Sprinkler - hydrogen fire



# Thank you for your attention.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