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Hydrogen Behavior and Mitigation Measures: State of Knowledge and Database from Nuclear Community

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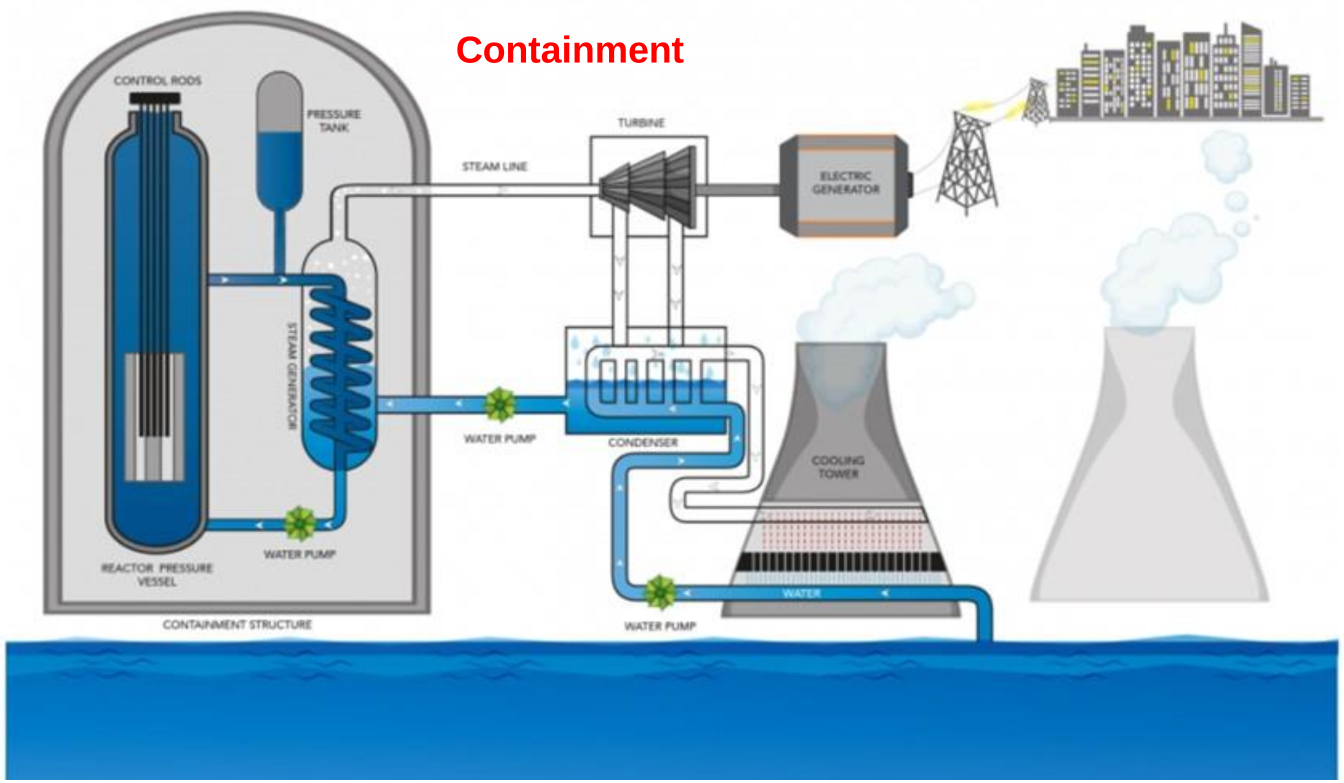
AFP/GETTY - H_2 explosion at Fukushima March 11, 2011

Outline

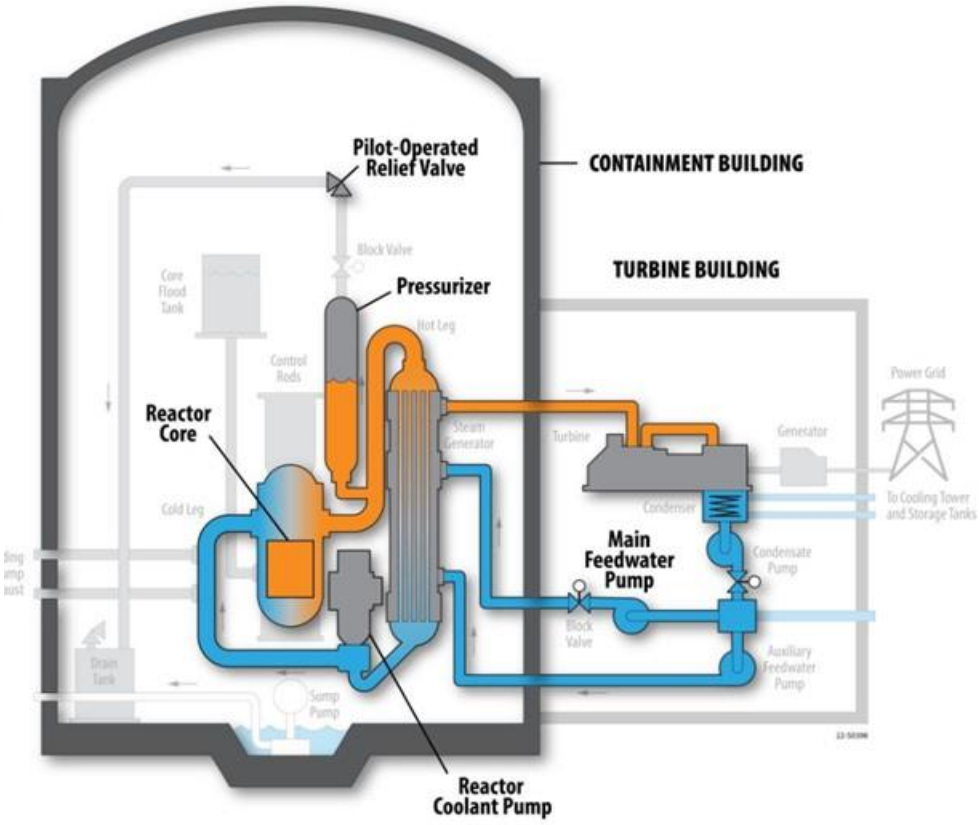
- Nuclear hydrogen safety
- R&D focus and evolution
- State of knowledge & Large-scale facilities
- Open issues and linkage to other industries



Schematic of Pressurized Water Reactor
[Graphic by Sarah Harman – U.S. Department of Energy]

Hydrogen Safety for Nuclear Reactors

- **Hydrogen can be produced from various sources in loss of coolant accidents**
  - ➢ Metal-steam reaction, molten core concrete interaction, water radiolysis
- **1979 Three Mile Island accident**
  - ➢ Estimated 4,500 m^3 H_2 were generated by metal-steam reaction → H_2 deflagration occurred inside the containment → no damage to containment
- **2011 Fukushima Daiichi accident**
  - ➢ Estimated 5-10,000 m^3 H_2 per reactor were generated → H_2 deflagration/detonation damaged three reactor buildings

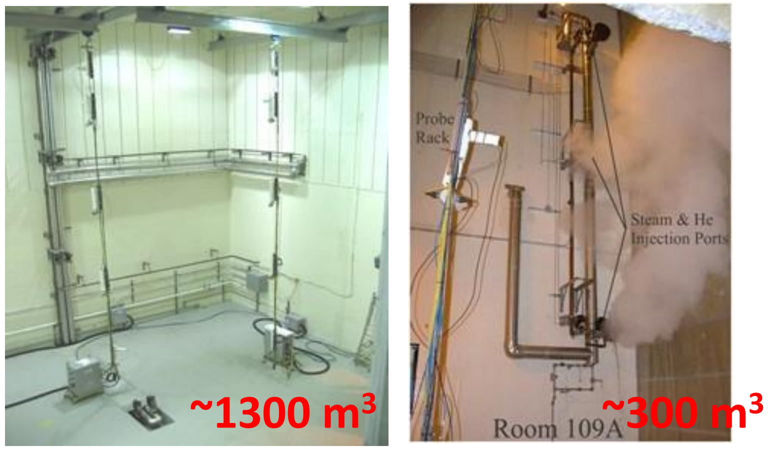


Schematic of TMI-2 Reactor

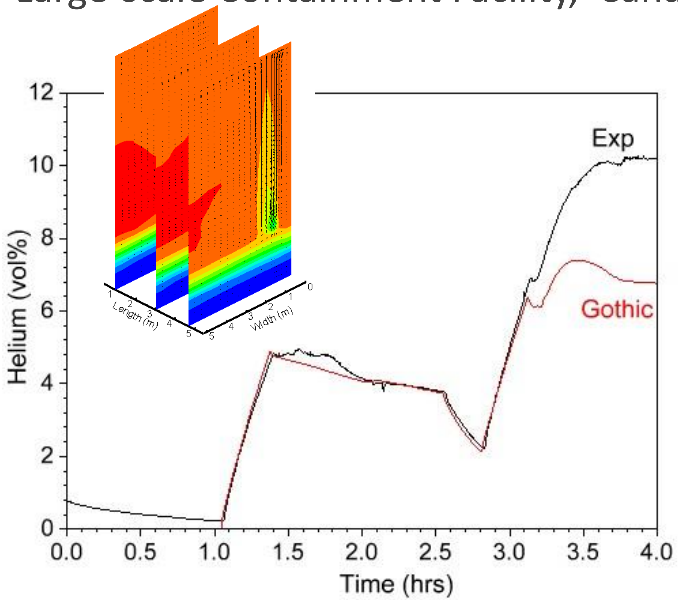
Focus of Nuclear Hydrogen R&D

- **Large-scale experiments**
  - Light gas transport and mixing behavior
  - Hydrogen combustion dynamics in various regimes
  - Mitigation devices qualification/assessment
- **Computer model development and validation**
  - Integral lumped parameter codes (e.g., ASTEC, MAAP, MELCOR, SPECTRA) for system analysis with simple physics and models
  - 3D/CFD codes (e.g., GOTHIC, GASFLOW, Fluent, OpenFOAM) for detailed containment analysis

Ultimate goal is to maintain containment integrity in severe accidents!



Large-scale Containment Facility, Canada



Z. Liang et al., 19th PBNC,2014

Evolution of Hydrogen R&D in Nuclear Community

Fundamental Understanding	Model Development	Engineering Solutions	Safety Enhancement
1980-1990	**1990-2000**	**2000-2010**	**2011-2022**
• H_2 gas mixing behavior • H_2 combustion physics & fundamentals • H_2 mitigation strategy development	• Thermohydraulics, H_2 transport & gas mixing • H_2 combustion safety criteria & dynamics • PAR qualification	• H_2-air-steam gas mixing & combustion in complex geometries • CFD-grade database • PAR performance	• Effects of safety systems (spray, fan-cooler, rupture dices) on H_2 behavior • PAR behavior in severe accidents

Knowledge Base on Hydrogen Distribution

- **Key phenomena and areas of interest:**
  - Turbulence, buoyancy, condensation, natural & forced convection
  - Stratification formation and break-up
  - Interaction with engineering systems (e.g., air cooler, spray, venting, recombiner)
- **Key parameter – volume Richardson number [1]:**

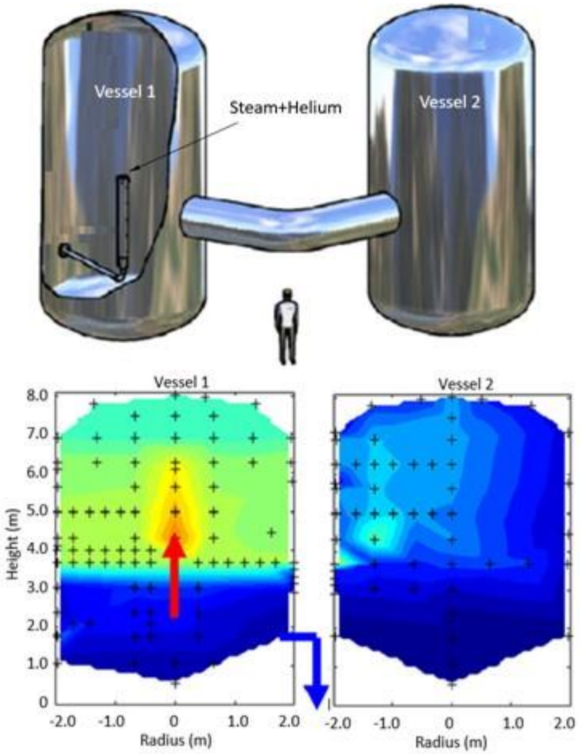
$$Ri_V = g\left(\frac{\rho_{H2}}{\rho_{air}} - 1\right)\frac{{V_{enclosure}}^{1/3}}{{U_{H2}}^{2}}$$

- **Status of knowledge:**
  - Numerous light gas mixing tests exist in various scales[2]; recent research is directed to provide “3D” data for validation of 3D/CFD codes
  - Considerable stratification with local high hydrogen concentration remains a concern
  - Effectiveness of engineering systems and potential negative impacts on gas mixing (e.g., reducing steam inertisation of the atmosphere) have been studied

[1] R. P. Cleaver, J. Hazard. Mater, 36, 1994, [2] NEA/CSNI/R(99)16

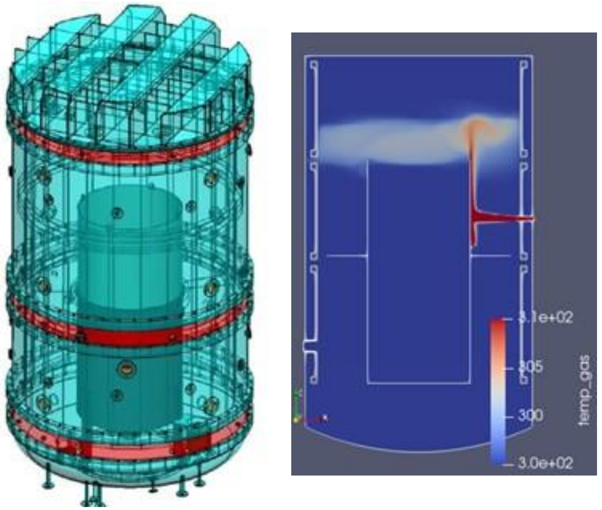
Hydrogen Gas Mixing Facilities and Benchmarks

PANDA (4 interconnected vessels)
90 m^3 each, H=4 m, D=4 m
PSI – Switzerland, 1995



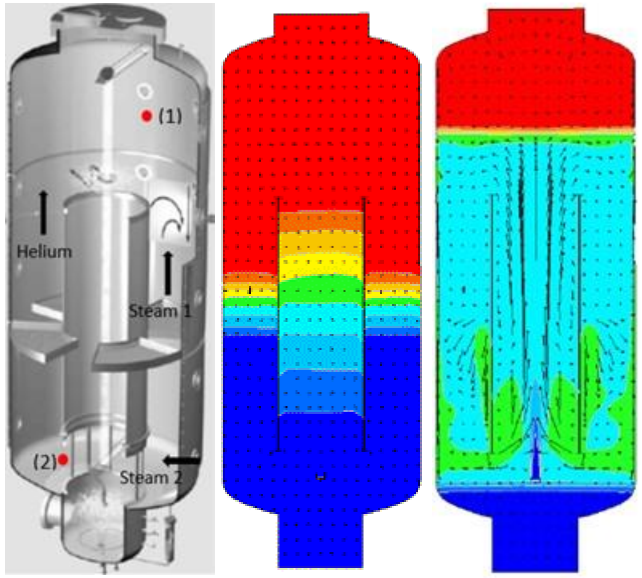
OECD/NEA SETH project [1]

MISTRA (2 nested vessel)
100 m^3, H=7.4 m, D=4.2 m
CEA – France, 1999



OECD/NEA HYMERS project [2]

THAI (1 or 2 regions)
60 m^3, H=9.2 m, D=3.2 m
BT – Germany, 2000



Fluent simulation

OECD/NEA THAI project – stratification and erosion of light gas [3]

[1] D. Paladino et al., Nucl. Eng. Des., 240 (2), 2010
[2] E. Studer et al., NUTHOS-12, 2018
[3] H.J. Allelein et al., NEA/CSNI/R(2007)10, 2007

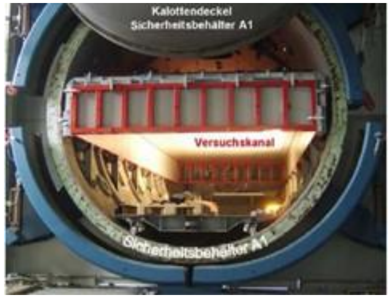
Knowledge Base on Hydrogen Combustion

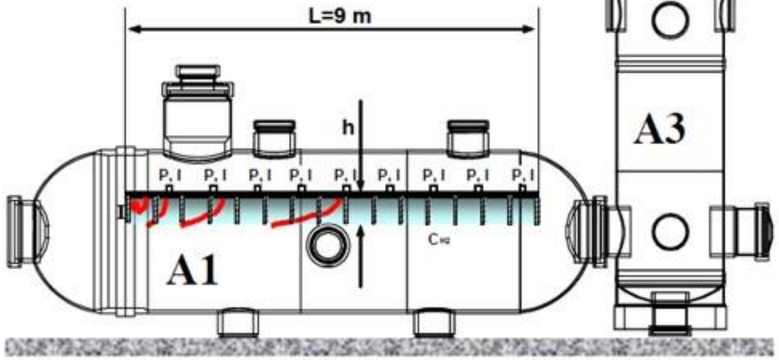
- **Key phenomena and areas of interest:**
  - Flammability limits, combustion regimes, flame instabilities
  - Laminar/turbulent flame speeds, thermodynamic and kinetic properties
- **Key parameters:**
  - Laminar/turbulent burning velocity, flame thickness, criterion for flame acceleration and deflagration-to-detonation transition (DDT)
- **Status of knowledge:**
  - Early studies in the 80's and 90's established a foundation for development of flame acceleration and DDT criteria[1]
  - Recent studies are mainly motivated to provide new data for model development and code validation (e.g., ISP49[2])
  - Critical parameters for non-homogeneous mixtures and interaction with engineering systems (e.g., spray) have being studied[3]

[1] NEA/CSNI/R(2000)7, [2] NEA/CSNI/R(2011)9, [3] Home - AMHYCO

Hydrogen Combustion Facilities and Benchmarks

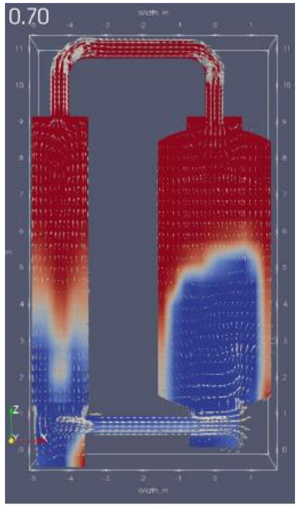
Large-scale interconnected vessels
110/30 m^3, 100/60 bar
KIT – Germany, 2010





Combustion in Semi-Confined Flat Layer [1]

THAI+ (2 vessels), 14 bar
18/60 m^3, H=9.2 m, D=1.5/3.2 m
BT – Germany, 2015



GOTHIC simulation

OECD/NEA THAI3 project – combustion in interconnected vessels [2]

ENACCEF2, H=7.7 m, D=0.23 m, 240 bar
ICARE CNRS – France, 2016

ETSON-SAMHYCO-NET project – flame acceleration & DDT [3]

[1] M. Kuznetsov et al., Nucl. Eng. Des., 286, 2015
[2] S. Gupta et al., Front. Energy 15, 2021
[3] A. Bentaib et al., NURETH-19, 2022

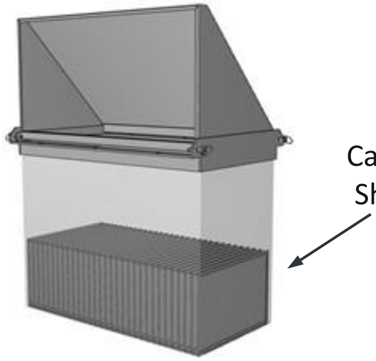
Hydrogen Management for NPPs

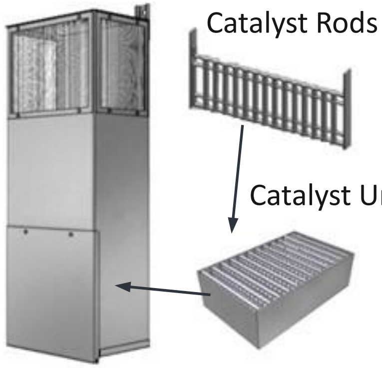
- **Regulations for hydrogen management:**
  - Prevent uncontrolled releases and dispersion of nuclear substances
  - Limit the consequences of an accident
- **General accident management strategies** [1]**:**
  - Step 1: reduce the possibility of hydrogen accumulation to flammable concentrations
  - Step 2: minimize the volume of gas at flammable concentrations if flammable concentrations cannot be precluded
  - Step 3: prevent further increasing hydrogen levels from the flammable to detonable mixture concentrations

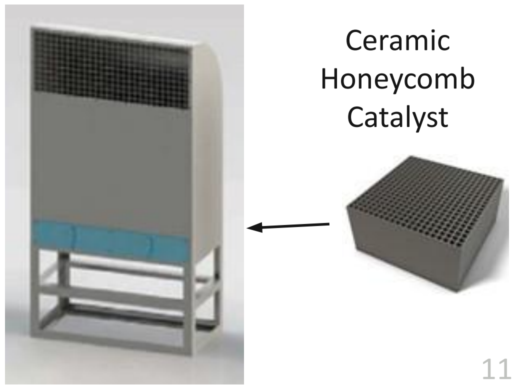
[1] NEA/CSNI/R(96)9

Mitigation Measures Implemented in NPPs

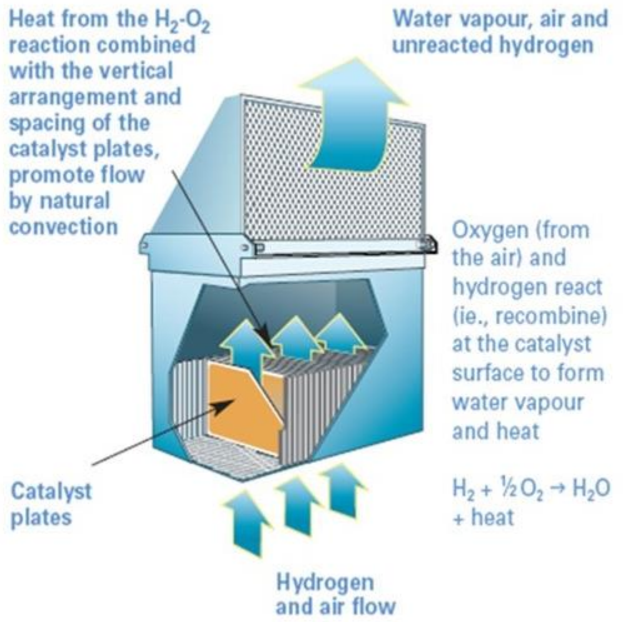
- **Common hydrogen mitigation measures:**
  - Deliberate ignition, consumption/recombination of H_2 , replacement of O_2 by inert gas, atmosphere dilution, filtered containment venting
- **Igniter**
  - Prevent "damaging burns" by ignition at near lean flammability limits
  - Can handle higher H_2 flow rates, need to be appropriately located, need external power
- **Passive Autocatalytic Recombiner (PAR)**
  - Self-start/stop, no need for external power
  - Subject to mass transfer limitations and may cause ignition at 6-7% H_2 in air

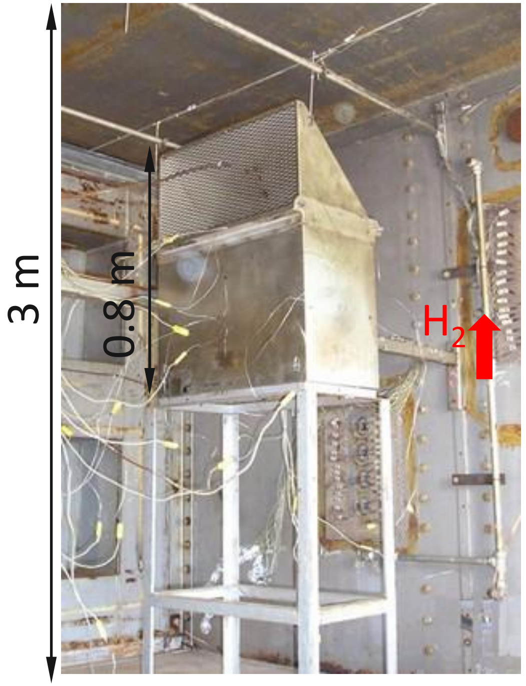


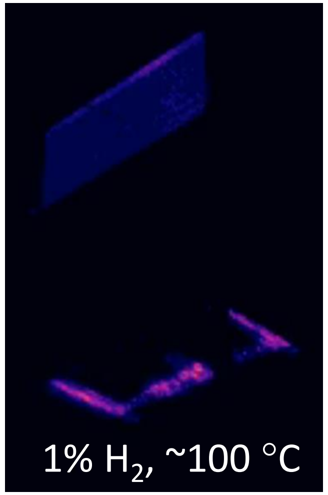


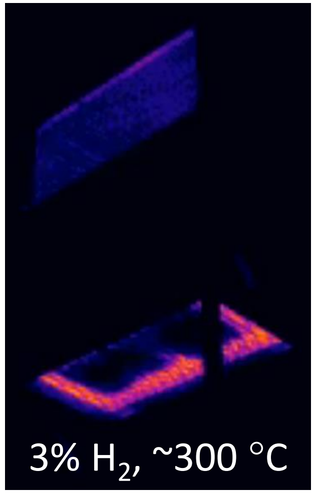


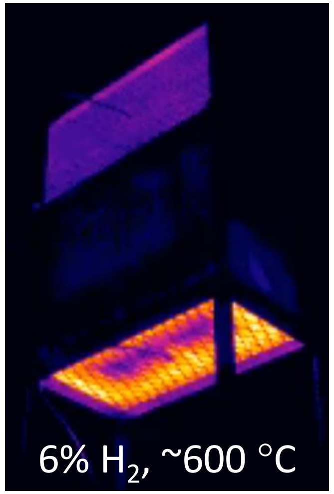
Passive Autocatalytic Recombiner (PAR)



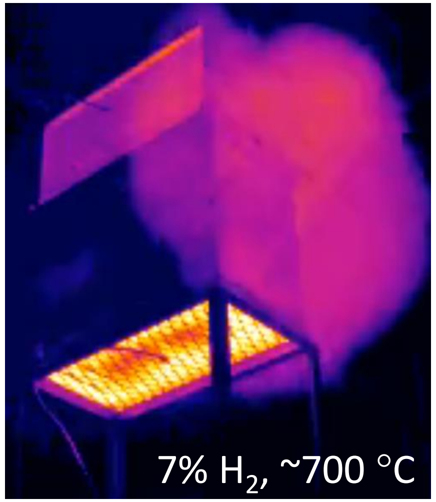






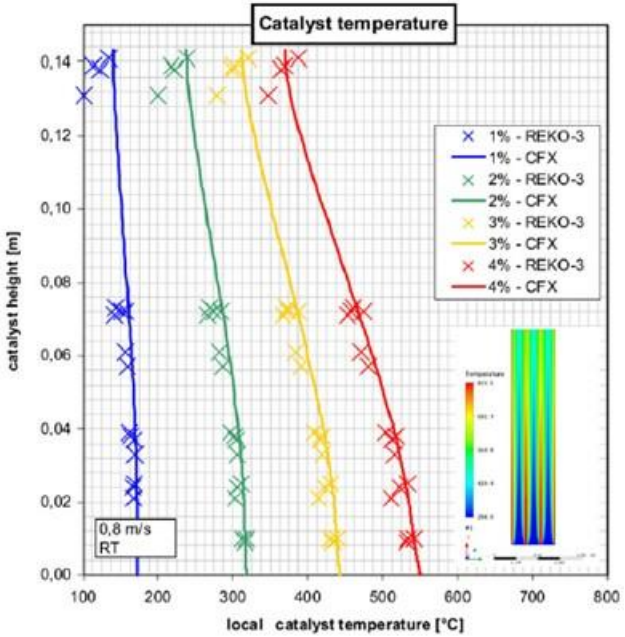


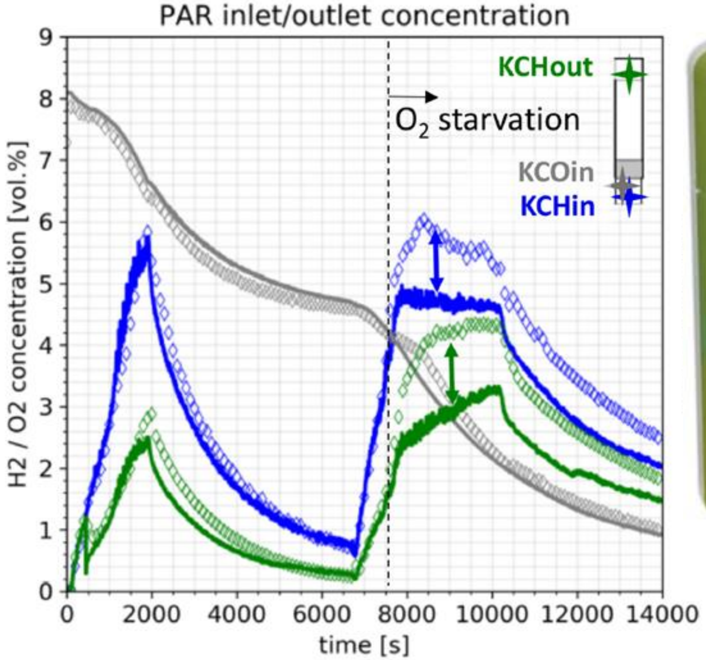
- H_2 release rate >> PAR recombination rate → ignition at ~7% H_2
- Ignition at extremely lean mixtures: **Good or Bad?**



PAR Testing Facilities and Benchmarks

REKO Facilities, Juelich – Germany





THAI

Forced flow, well-defined, steady-state, catalyst sample

Pressure vessel 5.3 m^3, H=4 m, D=1.4 m full-size PAR

Coupling of a 2D mechanistic PAR model with CFD code [1]

Validation of containmentFOAM using large-scale PAR tests conducted in THAI facility [2]

[1] E.-A. Reinecke et al., Nucl. Eng. Des., 52, 2010, [2] S. Kelm et al., Fluids, 6, 100, 2021

Open Questions and Linkage with Other Industries

- **Scaling effects**
  - Height of test facilities: 8-10 m, an order of magnitude smaller than nuclear containments
- **Safety criterion & combustion behavior**
  - Slow flame, fast flame, DDT
  - Non-homogeneous/stratified mixtures, unconfined mixtures
  - Complex geometry, multi-connected rooms
  - Interaction with mitigation systems (e.g., spray, venting)
- **Computer codes**
  - Uncertainty/accuracy, user effects, applicable ranges, validation
- **Coupling or co-locating** of a nuclear reactor with hydrogen production installations

Questions?

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