IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Contribution of recent R&D programs to hydrogen management improvement

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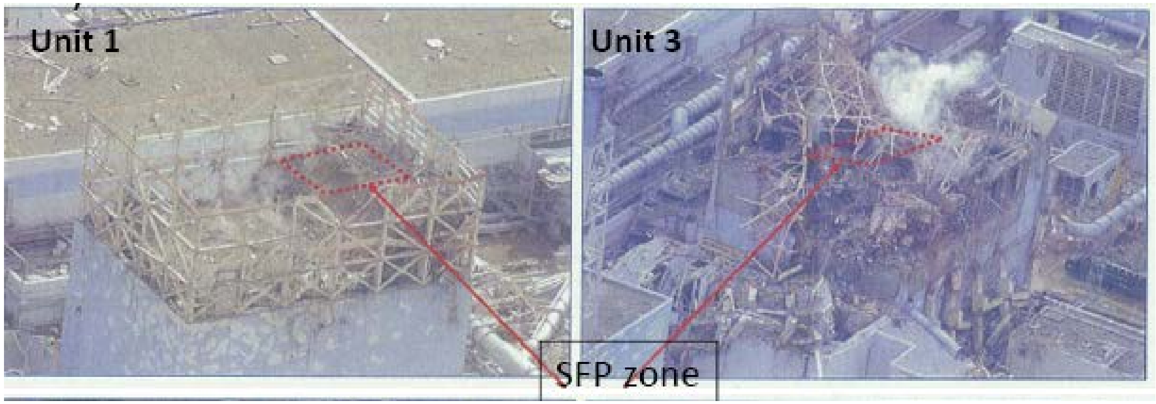
Severe accident and hydrogen explosion in NPP

Three Mile Island Nuclear Power Plant

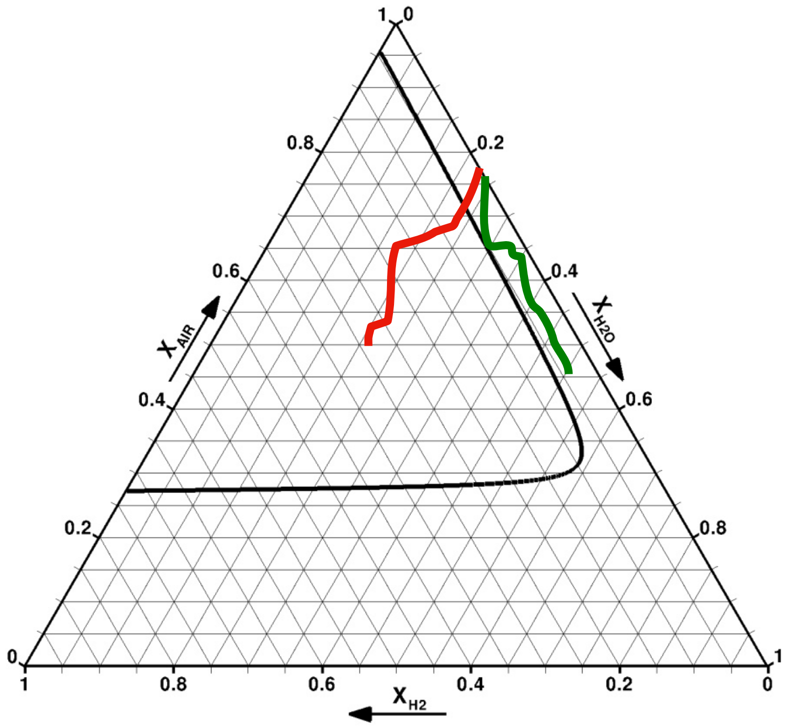
Hydrogen explosion during Fukushima accident



Hydrogen risk mitigation strategies

Limiting oxygen c

Limiting hydrogen



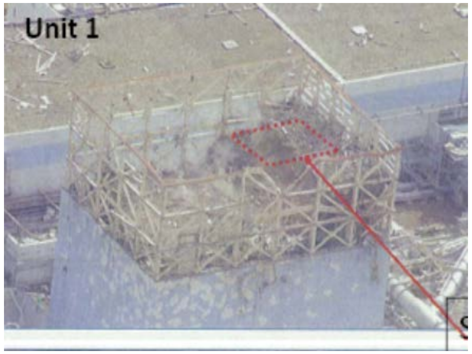
Dilution using large volume

ıdopted for
ɩkushima NPPs)

ıdopted for
s and LWRs

/ adopted for
French PWRs

H2 control system implementation



Distribution

PARs operation

Combustion

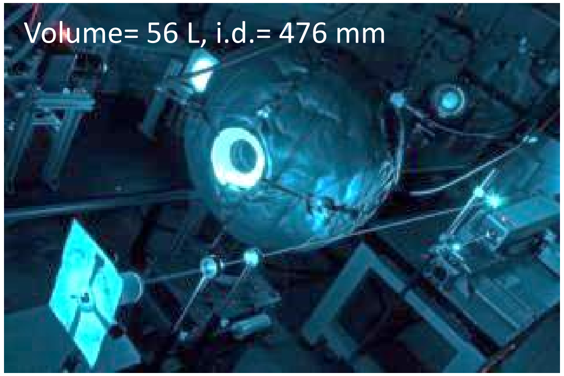
Structure response

Combustion

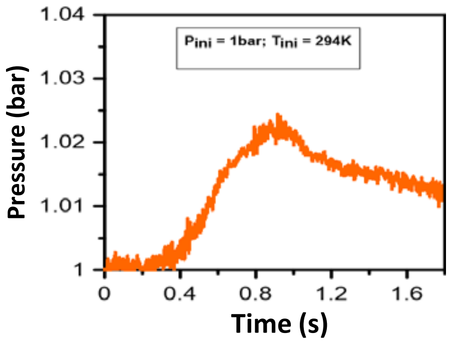
- Flammable mixture conditions
- Potential Ignition sources
- Characterization of flame propagation from early stage to accelerate regime
- Perspectives:
  - Hydrogen monitoring system development
  - Enhancement of SAMG

identification of flammable mixtures

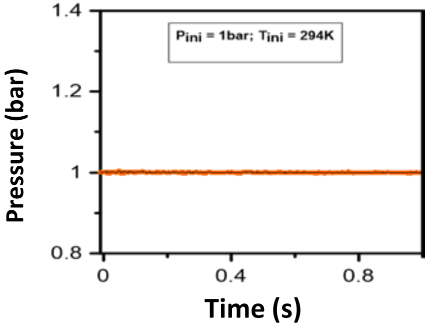
H_2/Air flammability limits – quiescent conditions, Spherical bomb method at ICARE CNRS

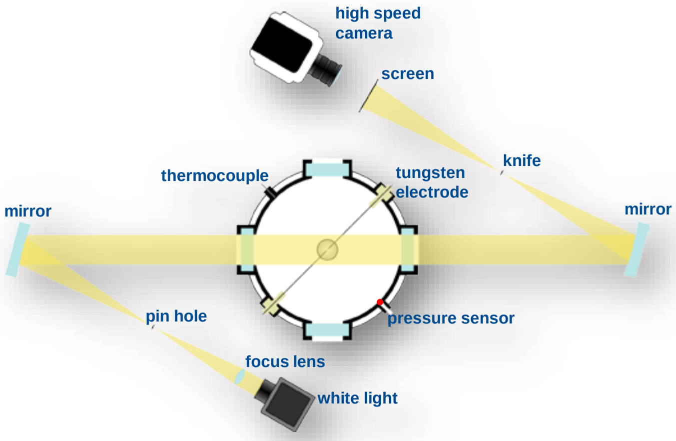


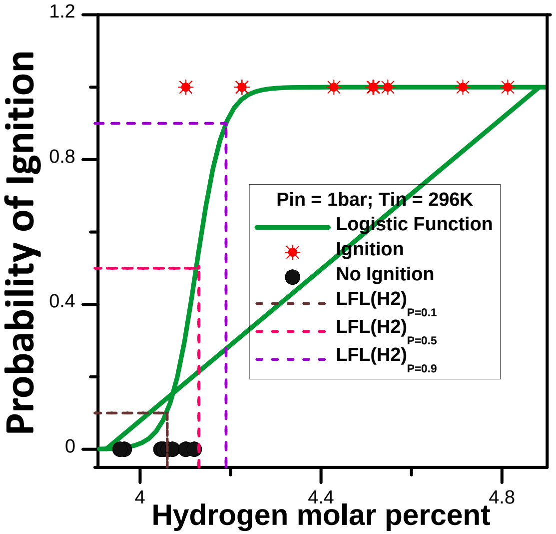
Ignition



No Ignition



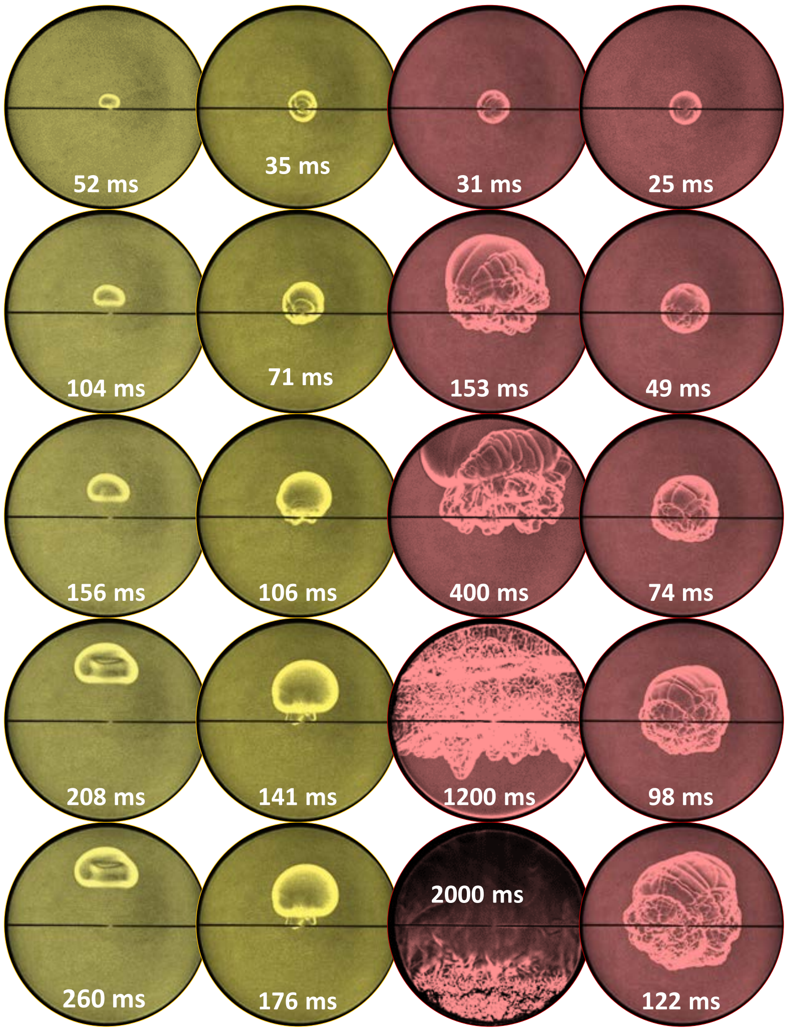


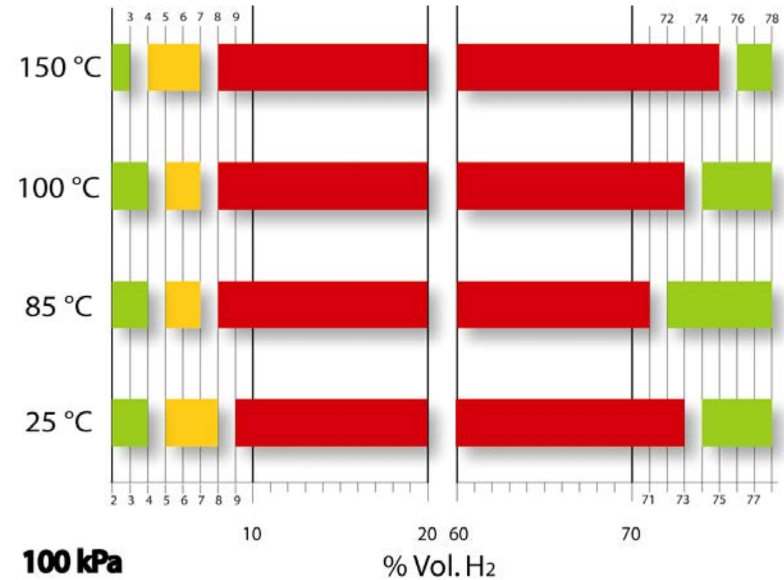


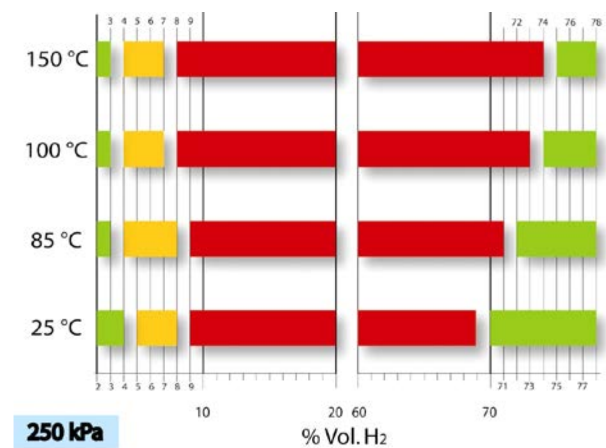
K. N'Guessan, A. Commandini, M. Idir, J. Pavageau, T. Cuvillier, N. Chaumeix, Evaluation of flammability limits of H_2/O_2 mixtures in conditions relevant to nuclear waste transportation: Pressure and nitrogen effects, ICDERS 2017, Paper 1032, 2017

H$_2$/Air flammability limits – quiescent conditions

6% H$_2$ | 8% H$_2$ | 9% H$_2$ | 10 % H$_2$

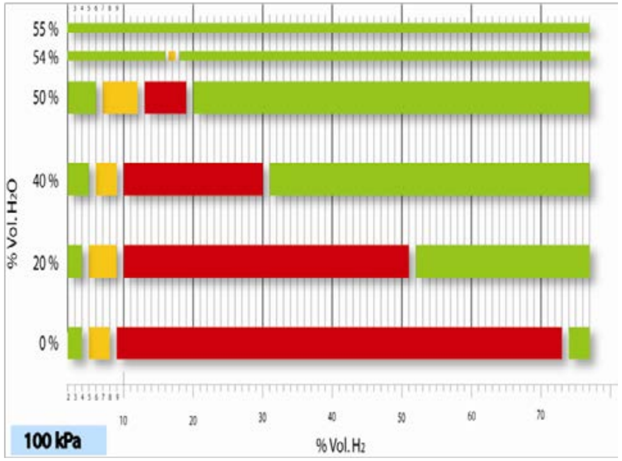


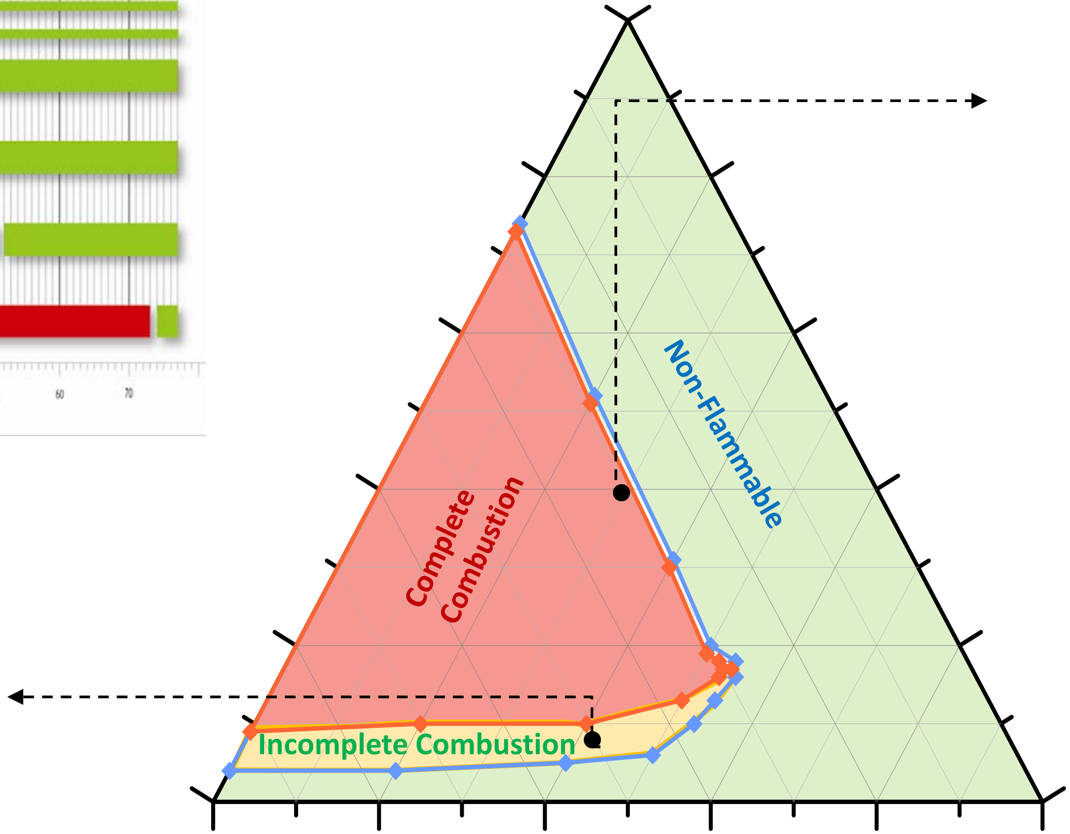




Cheikhravat, H., Chaumeix, N. , Bentaib, A., Paillard, C.-E., Flammability limits of hydrogen-Air mixtures, Nuclear Technology 178 (1), 2012, p. 5-16

❑ H_2/Air/H_2O_{vap} flammability limits – quiescent conditions





$0.40\ H_20 + 0.30H_2$
P_{ini} = 0.987 bar
T_{ini} = 100.0 °C

$0.50\ H_20 + 0.11H_2$
P_{ini} = 0.987 bar
T_{ini} = 101 °C

Cheikhravat, H., Chaumeix, N. , Bentaib, A., Paillard, C.-E., Flammability limits of hydrogen-Air mixtures, Nuclear Technology 178 (1), 2012, p. 5-16

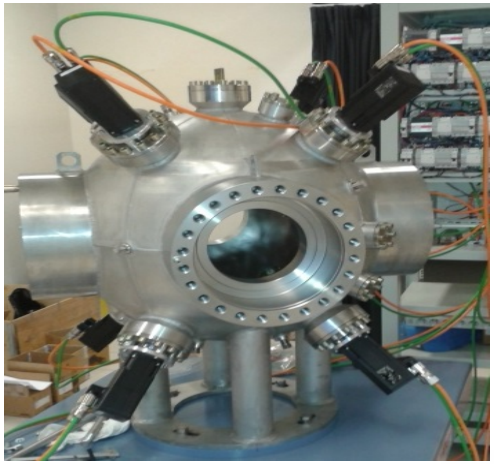
Question :

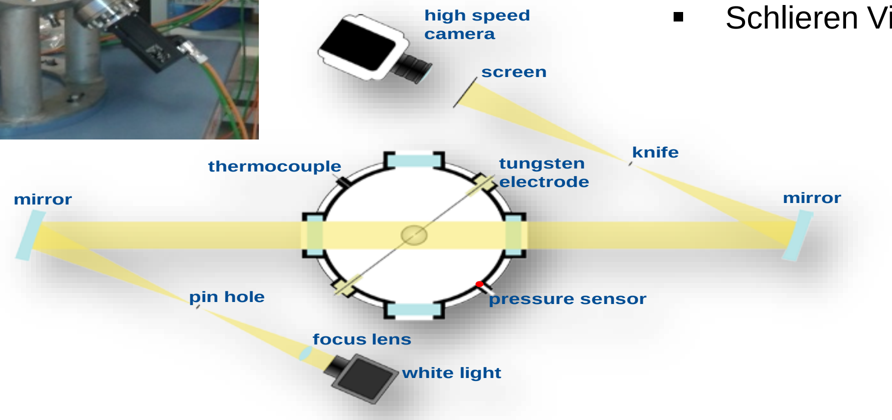
" if there is a certain gas motion in the vessel which can be represented by a given turbulence level, will it significantly affect the lower flammability limit?"

Flammability limits-turbulent conditions

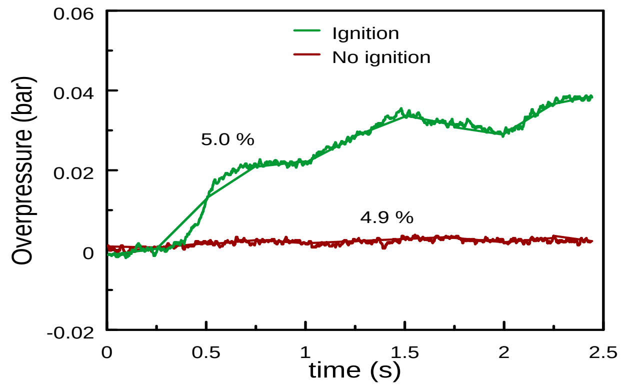
Spherical bomb method at ICARE-CNRS

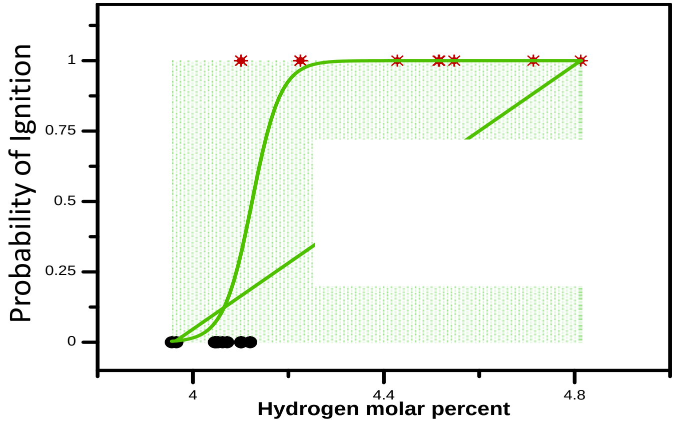
- Volume= 93 L
- T_{max}= 300 °C
- P_{max}= 200 bar
- i.d.= 563 mm
- ∅ visualization= 200 mm
- 8 fans
- 2 pressure transducers (Kistler 601A&6001)
- Schlieren Visualization

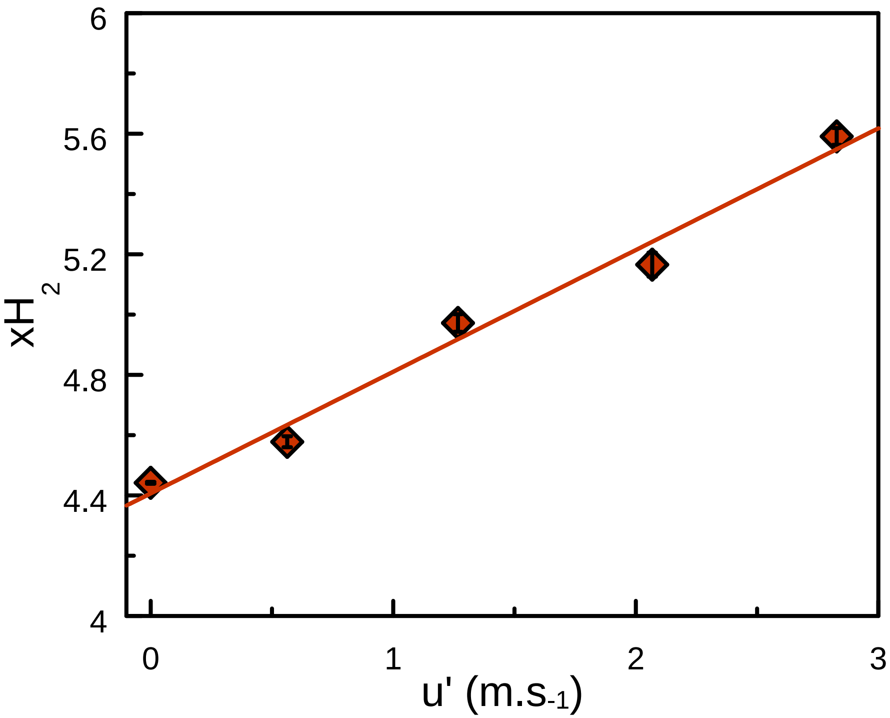




FLAMMABILITY LIMIT: initial turbulence effect







LFL increases linearly with the speed fluctuation

Goulier J., Chaumeix N., Meynet N. & Bentaïb A., Hydrogen Safety: Laminar and Turbulent Flame Speed of Spherical Flame in a Fanned-Stirred Closed Vessel, The 16th International Topical Meeting on Nuclear Reactor Thermal-hydraulics (NURETH-16), Chicago, Illinois, USA, 30 août au 4 septembre 2015

Question :

“In case of spray actuation, could we ignite gas-water droplets mixture and what could be the effect of spray on flammability limit?”

Spray flame interaction: Summary of PhD thesis

Could we ignite a gas-water droplet mixture ?

Step 1:

- Flammability Limits of H_2/air+ Mist of liquid Water (droplets)

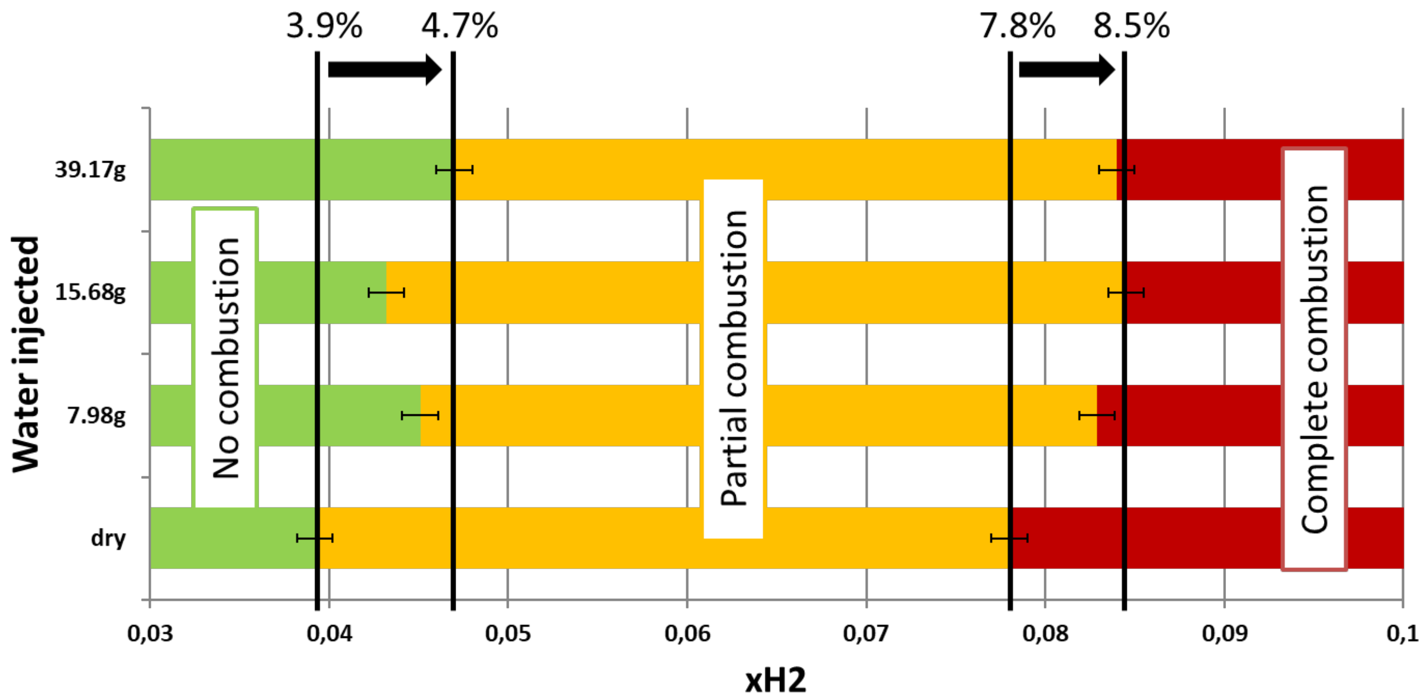
Step 2:

- Initial non-combustible mixture of $H_2/air/H_2O_{vap}$
- Activation of Water Spray
- Spark ignition activation

Results step 1 : Influence of water mist on flammability limits

Injection of water in a dry H_2/Air mixture
Bi-fluid nozzle
$D_{mean} = 5\ \mu m$

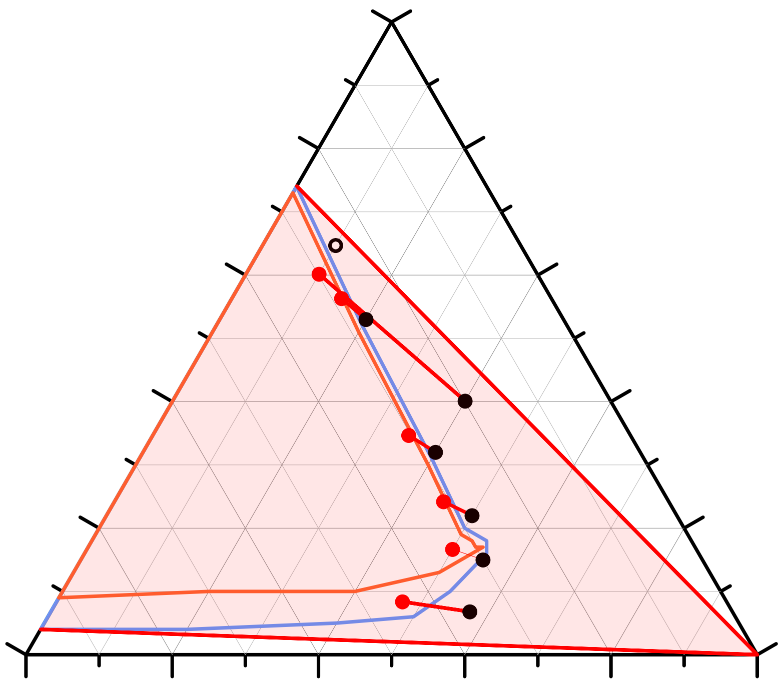
T = 298 K
P = 1 bar



H. Cheikhravat, **J. Goulier**, A. Bentaib, N. Meynet, N. Chaumeix, C.-E. Paillard, Effects of water sprays on flame propagation in hydrogen/air/steam mixtures, Proceedings of the Combustion Institute, Volume 35, Issue 3, 2015, Pages 2715-2722

Results step 2 : Mixture made flammable by water spray

T = 383 K - P = 1 bar
X_{H_2O} = 0.55, X_{H_2} = 0.15, X_{air} = 0.30
SMD = 75 µm



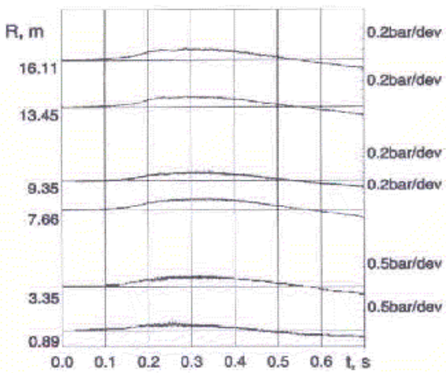
Domain of mixtures potentially ignitable by cooling from the spray

H. Cheikhravat, **J. Goulier**, A. Bentaib, N. Meynet, N. Chaumeix, C.-E. Paillard, Effects of water sprays on flame propagation in hydrogen/air/steam mixtures, Proceedings of the Combustion Institute, Volume 35, Issue 3, 2015, Pages 2715-2722

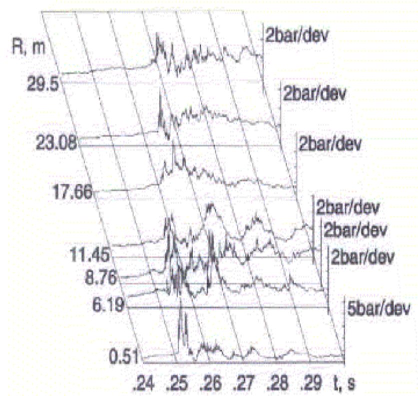
Flame propagation regimes

Flame acceleration (turbulence, instabilities…)

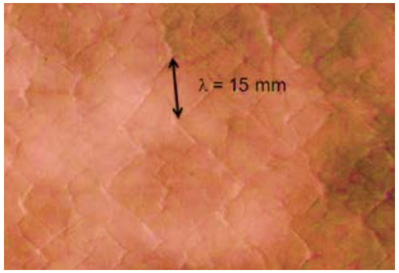
Transition from Deflagration to detonation regimes

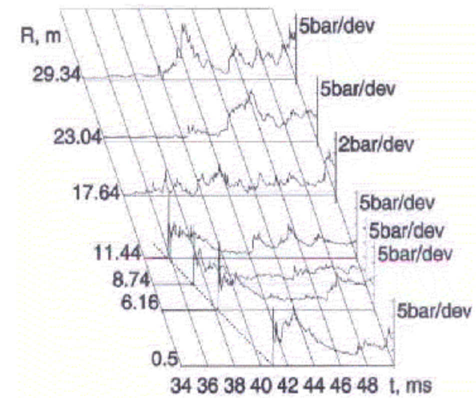


Slow Deflagration



Fast Deflagration

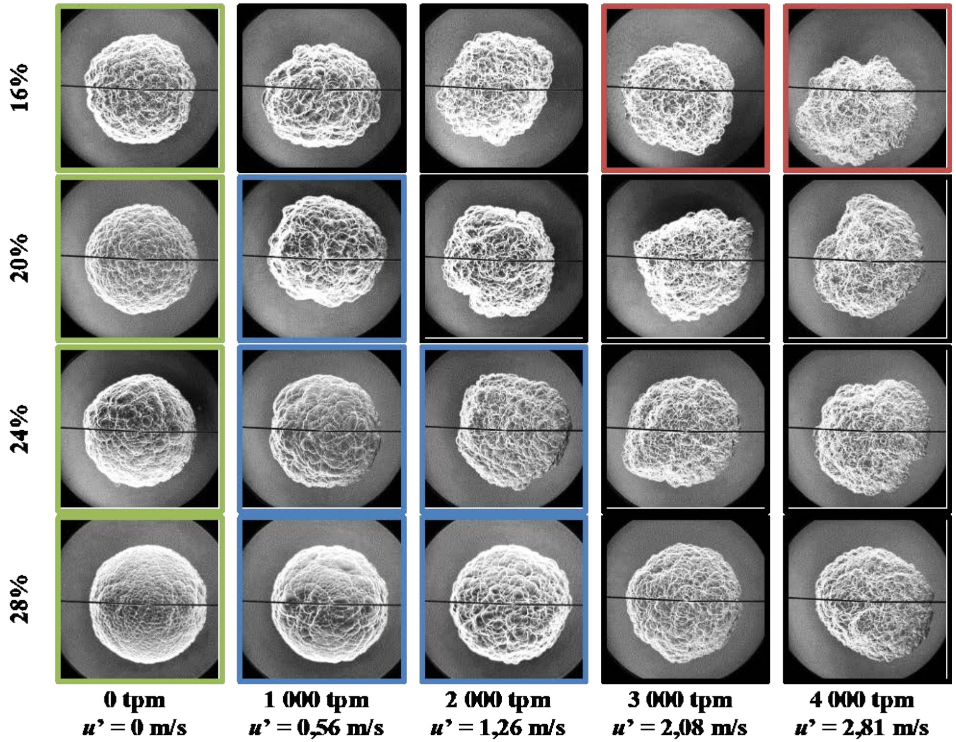




Detonation

TURBULENT COMBUSTION REGIME

Flame diameter
Ø = 120 mm



Green : laminar flames

Blue : wrinkled flamelets

Black : wrinkled flames with pockets

Red : thickened wrinkled flames

$$\frac{S_T}{S_b^0} = (1.61 \pm 0.01) \cdot \left(\frac{r_{flame}}{L_T}\right)^{0.333 \pm 0.002} \left(\frac{u'}{S_L^0}\right)^{0.526 \pm 0.002} (Le)^{-0.140 \pm 0.005}$$

GOULIER J., CHAUMEIX N., MEYNET N. & BENTAIB A., Hydrogen Safety: Laminar and Turbulent Flame Speed of Spherical Flame in a Fanned-Stirred Closed Vessel, The 16th International Topical Meeting on Nuclear Reactor Thermal-hydraulics (NURETH-16), Chicago, Illinois, USA, 30 août au 4 septembre 2015

On going Work

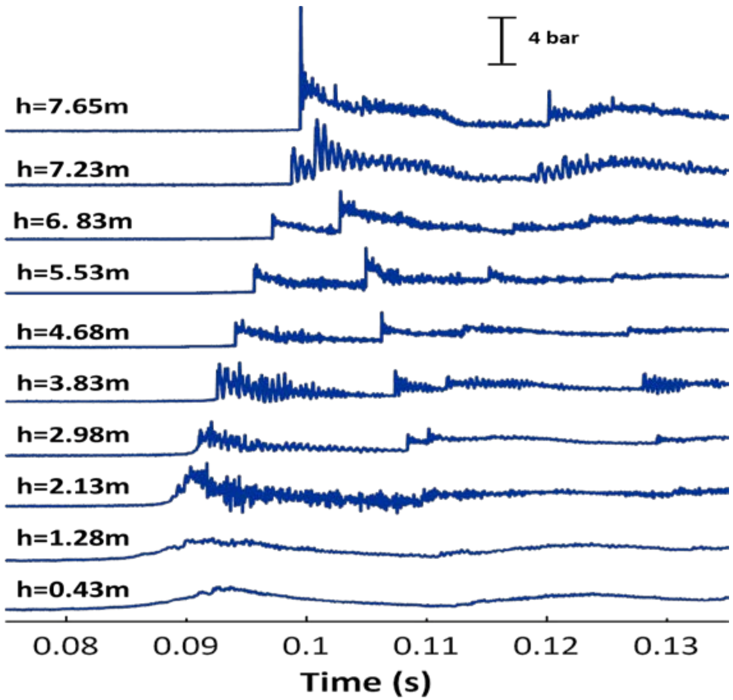
French National Program MITHYGENE

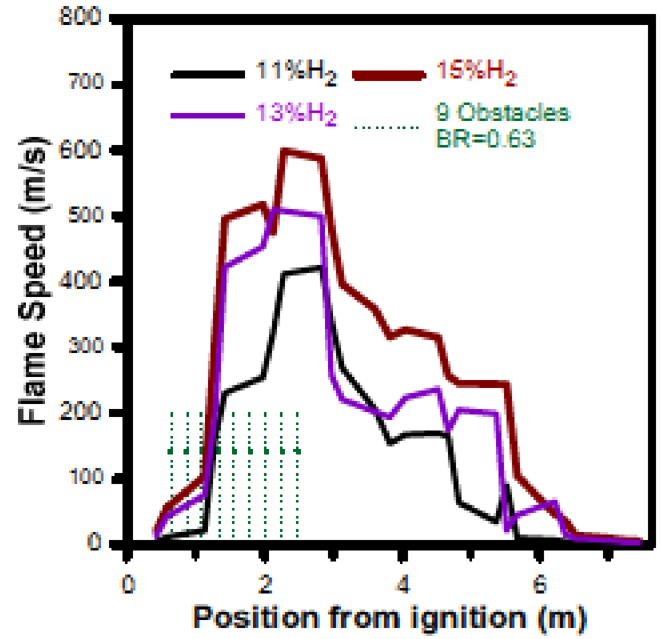
New Facility (8m high, 230 mm i.d.)
T_{ini} = 20 – 150°C ; P_{ini} = 1 to 3 bar
Pmax @ 20°C = 240 bar

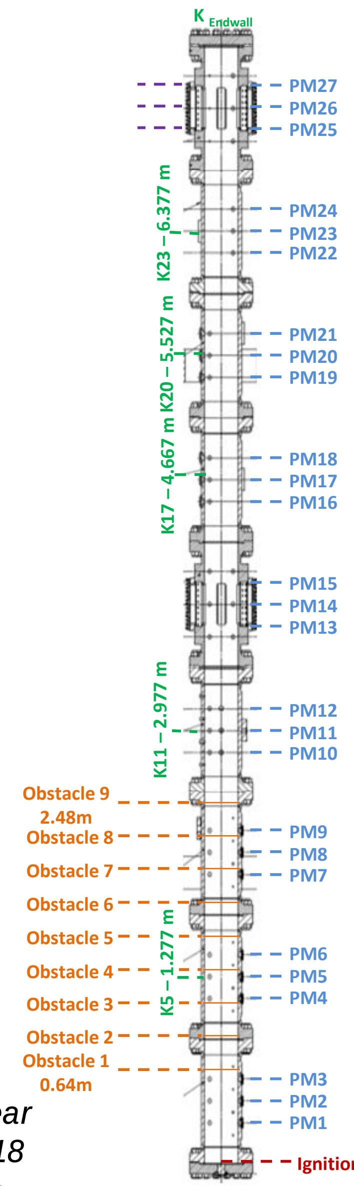
Highly instrumented to investigate

- **Flame speed, High speed Imaging**
- **Flow velocity induced by the flame (HS-PIV**
- **Effect of water vapor/spray**
- **Initial T & P relevant to severe accidents**

flame acceleration & flame-choc interaction







Effect of initial temperature,

Effect of initial gas composition

BENTAIB A. & al, ETSON-MITHYGENE benchmark on simulations of upward flame propagation experiment in the ENACCEF2 experimental facility, The 12th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics, Operation and Safety (NUTHOS-12) Qingdao, China, October 14-18, 2018

Towards the reactor application

PAR and flame behavior in Ex-vessel conditions
SAMHYCO-NET PROJECT (2017-2020)

Academic: ICARE, University Shanghai, NUT, UCSN
Research Institutes, TSO, Safety Authorities: IRSN, CEA, CIEMAT, LEI, SSTC-NRS, KAERI, KINS, PSI, IJS, NRG, JULICH, KIT, CNSC, JAEA, INRNE, SEC-NRS, SNERDI, CNL
Industrials: General Electric, EDF, AIR LIQUIDE, FRAMATOME

Main objectives

Objective 1: Review and critical assessment regarding :

- PARs experimental data and modeling
- H_2 and CO combustion experimental data and modeling

Objective 2: Experimental and analytical investigation of PARs behavior under ex-vessel conditions including the combined effect of oxygen starvation, steam, carbon monoxide and iodine

Objective 3: Experimental and analytical investigation of $H_2/CO/H_2O$ combustion under representative ex-vessel conditions

Objective 4: Improving the predictability of the numerical tools used for explosion hazard evaluation inside the reactor containment

Conclusion

- Flammable mixtures identification
- PARs ignition limits identification
- Flame propagation characterization
  - Assessment of the self-acceleration flame due to thermo-diffusive instabilities
  - Flame acceleration to initial turbulence
- Improvement of combustion modeling based on new well instrumented data
- Application to reactor Scale
- Perspectives

AMHYCO PROJECT

AMHYCO

Enhancing H_2 & CO Combustion Risk Management

AMHYCO project overview

SNETP FORUM, TS1-Long Term Operation & Construction, Online, February 3rd 2021

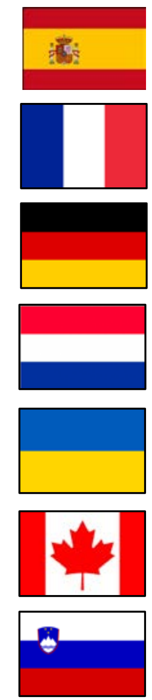
This project has received funding from the European Union's EURATOM Horizon 2020 research and innovation programme grant number: 945057. The content of this document reflects only the author's view. The European Commission is not responsible for any use that may be made of the information it contains.

AMHYCO general data

- Full Project Name: Towards An Enhanced Accident Management Of The Hydrogen/CO Combustion Risk
- EURATOM Work Programme 2019 "NFRP-02: Safety assessments for Long Term Operation (LTO) upgrades of Generation II and III reactors"
- Project No: 945057
- Start Date: 01/10/2020
- Project Duration: 48 months
- EU contribution: 3 974 402.50 €

AMHYCO partners

#	Participant organisation name	Country
1 (Coordinator)	Universidad Politécnica de Madrid (UPM)	Spain
2	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)	Spain
3	L'Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	France
4	Centre National de la Recherche Scientifique -Orleans (CNRS)	France
5	Forschungszentrum Jülich (FZJ)	Germany
6	Framatome GmbH (FRG)	Germany
7	Ruhr-Universität Bochum (RUB)	Germany
8	Jožef Stefan Institute (JSI)	Slovenia
9	Energorisk, Ltd. (ER)	Ukraine
10	Nuclear Research and Consultancy Group (NRG)	Netherlands
11	Canadian Nuclear Laboratories (CNL)	Canada
12	LGI Consulting (LGI)	France



AMHYCO objectives

The AMHYCO project main objective is **to propose innovative enhancements on the way combustible gases are managed in case of a severe accident in currently operating reactors.**

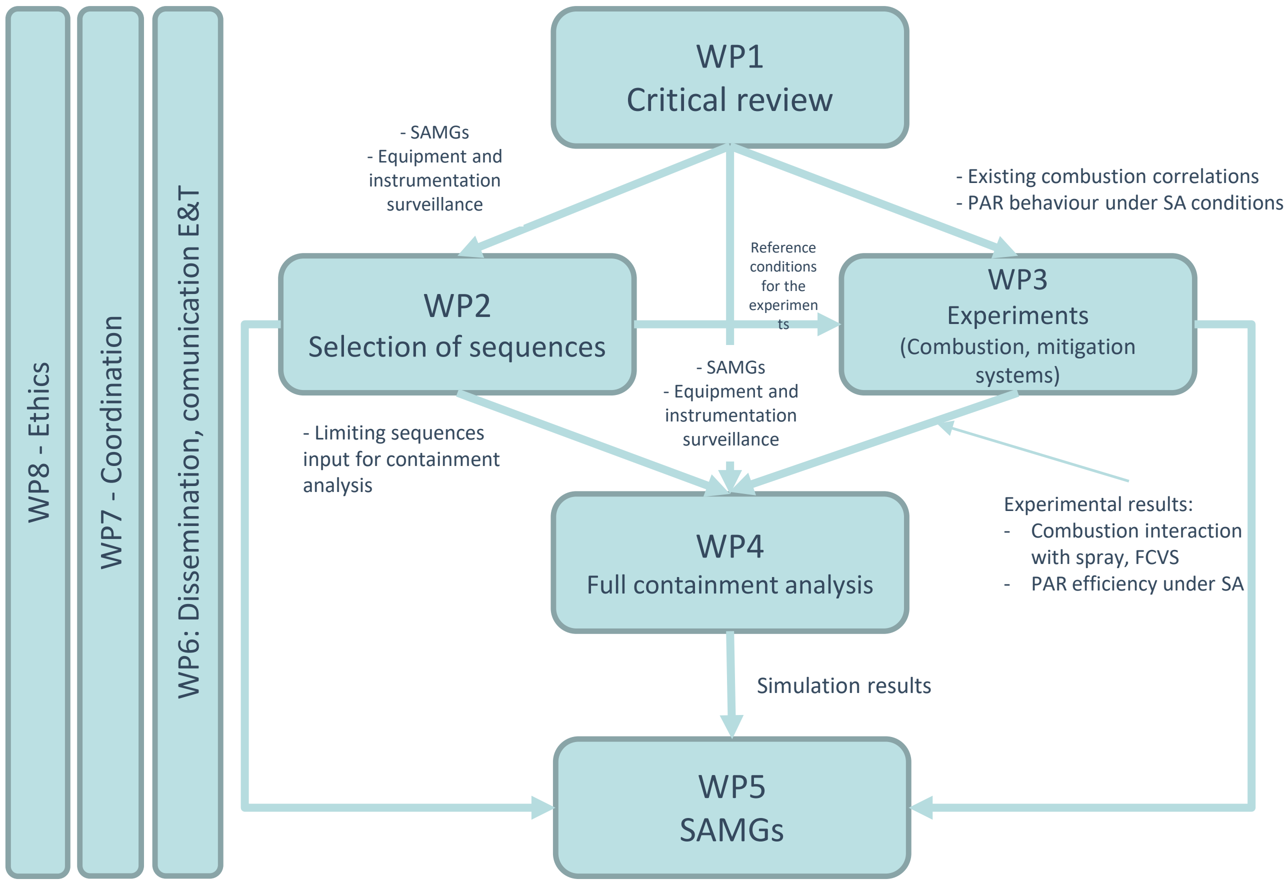
To reach this main objective, the AMHYCO project has three main specific objectives:

Objective 1: To experimentally investigate phenomena that are difficult to predict theoretically: H2/CO combustion and PARs (Passive Autocatalytic Recombiners) behavior under realistic accidental conditions, taking into account their interaction with safety systems. Reducing the uncertainties in the phenomena is a remarkable way of enhancing the severe accident safety.

Objective 2: To improve the predictability of analysis tools - Lumped Parameter (LP), 3D and Computational Fluid Dynamic (CFD) codes - used for explosion hazard evaluation inside the reactor containment and providing support to SAMGs design and development.

Objective 3: To improve the Severe Accident Management Guidelines for both in-vessel and ex-vessel phases with respect to combustible gases risk management, using theoretical, simulation and experimental results.

AMHYCO workflow



AMHYCO

AMHYCO Partners

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JÜLICH Forschungszentrum

framatome

RUHR UNIVERSITÄT BOCHUM RUB

Jožef Stefan Institute

ENERGORISK

NRG

Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

LGi sustainable innovation

17

Thank you for your attention!

For any questions or further information, please contact:

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