Session 9: General Aspects of Safety

Chair: Frank Markert (DTU); Participants and contributors: Bill Buttner (NREL), Eveline Weidner (EC-JRC), Frank Markert (DTU), Franck Verbecke (AREVA)

Research Priorities Workshop – 26/27 September 2016, JRC IET Petten, Netherlands

The Focal Point on Integrated Research and Information for Hydrogen Safety

Topics for priority workshop

- a) Hydrogen Safety Training
- b) Mitigation including sensor
- c) Human behavior

a) Hydrogen Safety Training (incl. c) Human behavior)

Status at the time of previous workshop

- „Hydrogen Safety Training", topic received rank 8 in 2014
- The following ranking of sub-topics was derived:

Topic Number	Topic	Number of Votes	% of Votes Received
8.4	Higher education in hydrogen safety engineering	16	17
8.10	Establish an international forum to facilitate discussion on FR training with a focus on user experiences, needs and products	11	12
8.9	Research issues identified by the Hydrogen Safety Panel's work on enclosures (i.e., ventilation, leak rates, explosion protection, separation distances, etc.)	10	11
8.7	First responder training	10	11
8.2	Fitter/operator training	9	10
8.8	Publication of textbooks in different areas of hydrogen safety	9	10
8.3	Identify better hydrogen leak rate data	8	9
8.11	Needs based on the NFPA Research Foundation Report	7	8
8.6	Establishment of European or International University of Hydrogen Safety	5	5
8.1	Identify minimum natural ventilation rates for enclosed space	5	5
8.5	Interaction of water spray and flame front	2	2

b) Mitigation Including Sensors

Status at the time of previous workshop

- „Materials Compatibility/Sensors", topic received rank 9 in 2014
- The following ranking of sub-topics was derived:

Topic Number	Topic	Number of Votes	% of Votes Received
9.1	Reliability testing and validation of sensors for specific applications	17	22
9.3	Sensor placement to maximize effectiveness in specific applications	16	21
9.7	Hydrogen – metals interaction studies need to be expanded to further alloys of interest, and fundamental research is still needed to understand the role of all parameters	12	15
9.5	Complex and overbearing code requirements/limited international harmonization	11	14
9.6	Improve understanding of embrittlement of hydrogen service candidate materials (metallic, non-metallic)	9	12
9.8	Degradation modeling	8	10
9.4	Reduce sensor cost and identify common performance metrics for cross-cutting applications	5	6
9.2	Introduce testing of sensors for high concentration releases	0	0

General Aspects of Safety – training
Mitigation including Sensors
Progress / Closed gaps

Educational and online interactive training (UU)

- International Curriculum on hydrogen safety training for First Responders (FRs)
- State-of-the-art in hydrogen safety science and engineering and develop science-informed training materials dedicated to FRs
- RCS-informed training materials
- Intervention strategy and tactics for assessing accident scene status and decision making

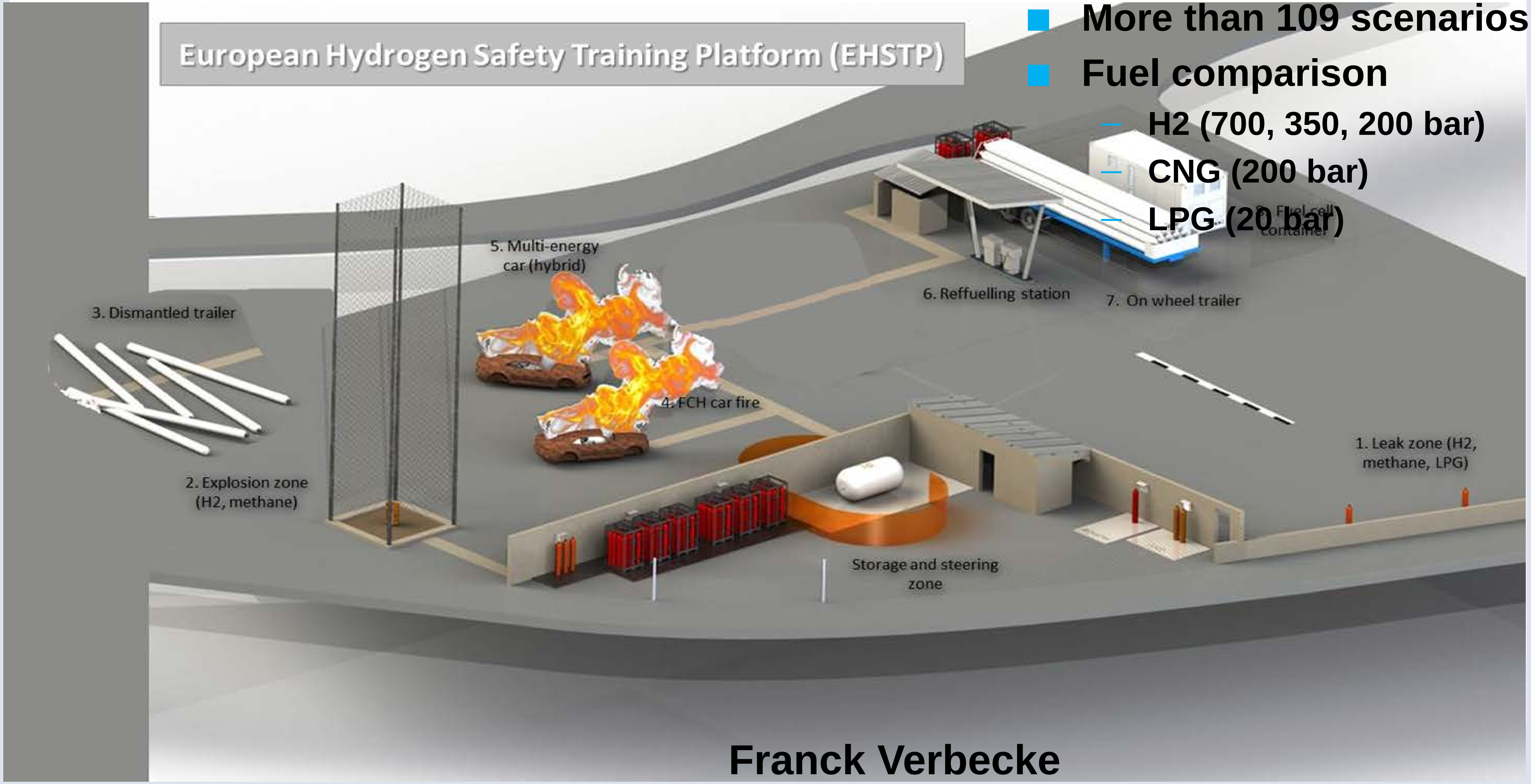
- ***Web-based course and exercises*** (to be delivered in September 2016)

Film on training

Operational training platform (AREVA)

Film on training

- **2500 m² platform**
- **More than 109 scenarios**
- **Fuel comparison**
  - **H2 (700, 350, 200 bar)**
  - **CNG (200 bar)**
  - **LPG (20 bar)**



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Operational training platform

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700 bar compressor and storages

Fuel cell platform

Jet fires platform

Technical area

700 bar car

Dismantled tube traile

Explosion platform

Pilot console

Film on training

Refuelling station

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Virtual Reality training platform (CRISE)

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Face-to-face training sessions

- 3 training sessions
- **71 trainees from 15 countries**
  Germany, Austria, Belgium, Croatia, Spain, USA, France, Italy, Norway, Netherland, Poland, Portugal, UK, Sweden, Czeck Republic
- **21 Observers from 10 countries**
  Germany, Belgium, Denmark, Spain, France, Netherland, Portugal USA, Japan, Taïwan
- **15 instructors or lecturers**.(partners and experts)

Emergency Response Guide

SOP	Acts or elementary actions	Objectives:
Reconnaissance	Identify	- Make contact with the safety manager of the installation to obtain clarifications concerning the incident; - Take into account the risk of an H_2 explosion in confined premises; - Take into account the risk of anoxia in confined premises.
	Forbid	- Forbid windward progression and imperatively establish an exclusion zone at 50 m; - Ban non-ATEX electrical or electronic apparatus in the exclusion zone (cell phones, beepers, walkie-talkies, etc.).
	Inspect	- Cut off external power sources in the building.
Rescue	Intervene Isolate	- **If confined premises and H_2 leak:** • wearing of isolating breathing apparatus (ARI) obligatory; • evacuate the victim outside of the exclusion zone as rapidly as possible. - **If risk of victim electrocuted:** • use emergency electrical hazard equipment to remove the victim; • avoid any contact between the rescuers and the electrical elements.
Establishment/ Attack		- Confirm or re-define the exclusion zone first (50m); - Perform measurements with an explosimeter (from the top to the bottom of the installation or storage system).
Protection		- **Actions with a risk of anoxia:** • close the H_2 supply valves; • ventilate the premises favoring natural drawing (do not use electrical or machine means of smoke removal). - **Actions with an electrical hazard** ➔ Actuate the emergency stop pushbutton (timeout of 20 min with presence of current remaining).
Removal Surveillance		- The surveillance phase ceases as soon as you are assured of the following: • the level of oxygen in the premise is normal (about 20%); • the absence of ATEX by explosimeter measurements; • the electrical installation is secured and taken in charge by a technician.

International collaboration

- International Association of Fire and Rescue Services (CTIF)
  - Commission “Extrication and New Technologie”
- European Fire Services

- Automotive car manufacturer
  - Toyota
- US DOE and PNNL
- HySUT (Japan)
- Taiwan

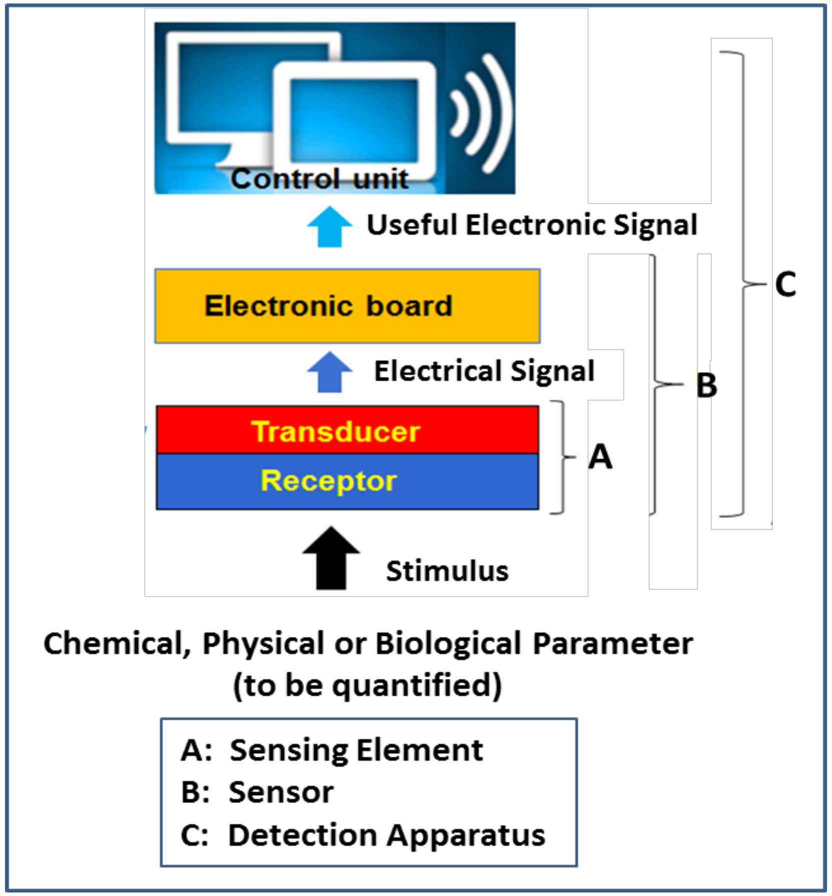
Common Commercial H_2 Sensor Platforms

Common Sensing Element Platforms

Features	Electrochemical Sensors EC	Combustible Gas Sensors CGS	Thermo-conductivity sensors TC
Transduction Mechanism	Faradaic e^- transfer (current)	Catalytic combustion (ΔR induced by ΔT)	Heat Transfer (ΔR induced by ΔT)
Advantages	Good LDL, Linear	Robust	Fast response time
Disadvantages	Prone to poisoning, drift	cross-sensitivity	non-selective (sensitive to $\Delta[H_2]$
Applications	Low level detection; personal monitors; ESIF	Industry Standard; HRS, Repair Facilities	Modeling studies; controlled environ., vehicles

Features	Metal Oxide Sensors MOX	Palladium Thin Film Sensors PTF	Hybrid Platforms HP
Transduction Mechanism	semiconductor doping (ΔR)	Sel. H_2 adsorption; multiple platforms	Multiple platforms (integrated)
Advantages	Low cost versatile sensor	Selectivity	Broad Range (LDL and UDL)
Disadvantages	Perceived instability; cross sensitivity	Prone to poisoning; still expensive	Limited availability (market support)
Applications	General Deployment; containers	Petroleum Industry, specialized applic.	Vehicle

Sensor vs. Sensing Element



All sensors are good
But none are good for all applications

Role of Sensors for Hydrogen Safety

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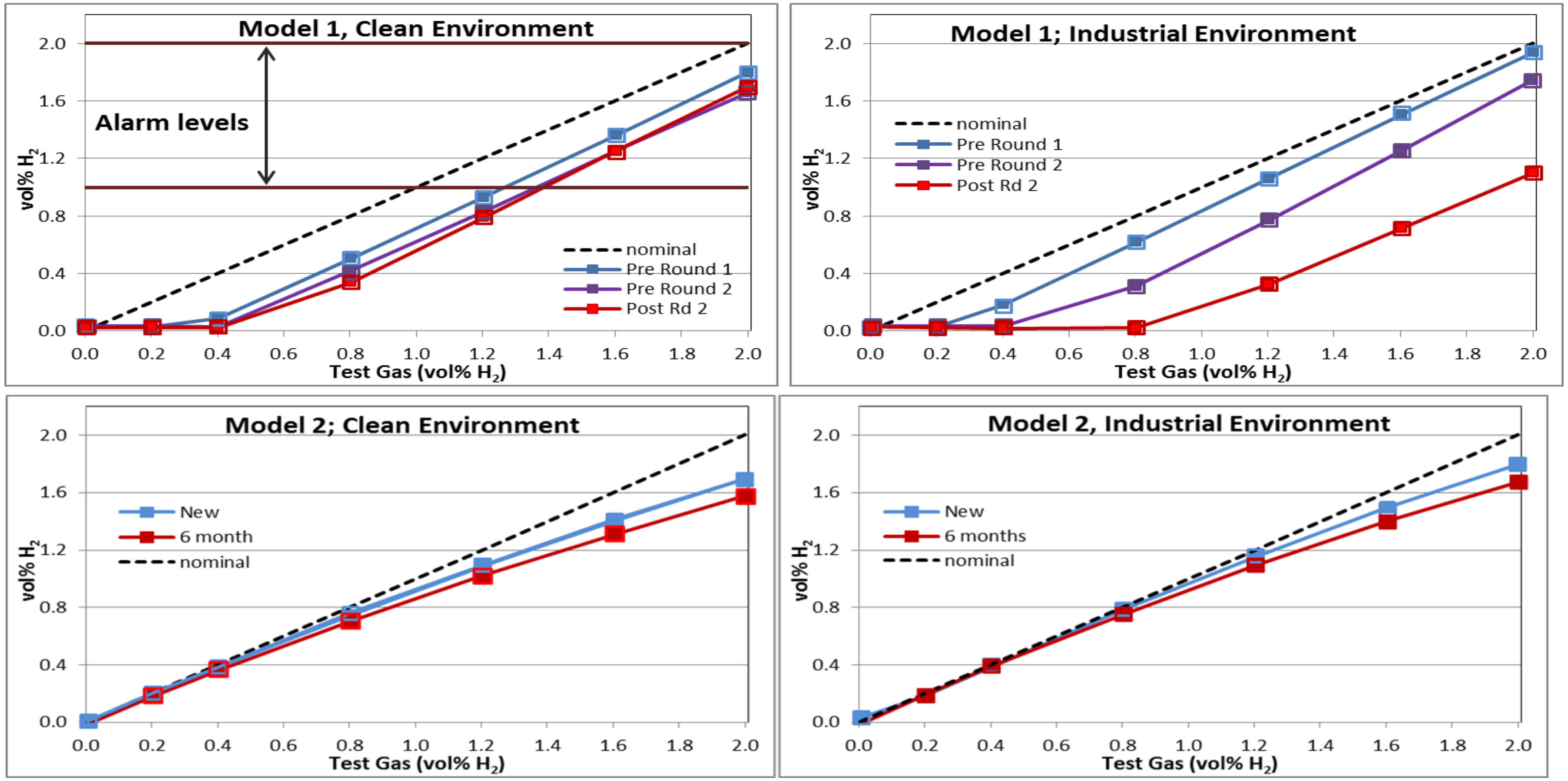
- Provide critical safety factor
  - Alarm at unsafe conditions
  - Ventilation activation
  - Automatic shutdown
- **Bad things can happen without sensors** [www.h2tools.org/lessons]
  - "Gaseous Hydrogen Leak and Explosion"
  - "Two False Hydrogen Alarms in Research Laboratory"
- **Relevant for Infrastructure and vehicle**
- **Mandated by code**
  - NFPA 2 and IFC
  - NFPA 2 is referenced in IFC
  - One approach to SIL compliance

A sensor will work only if used properly

HISTORICAL EVENT
(Abandoned Computer Center)

- Battery room for back up power (building damage)
- Hydrogen sensor was in audible alarm (ignored)
- link to case

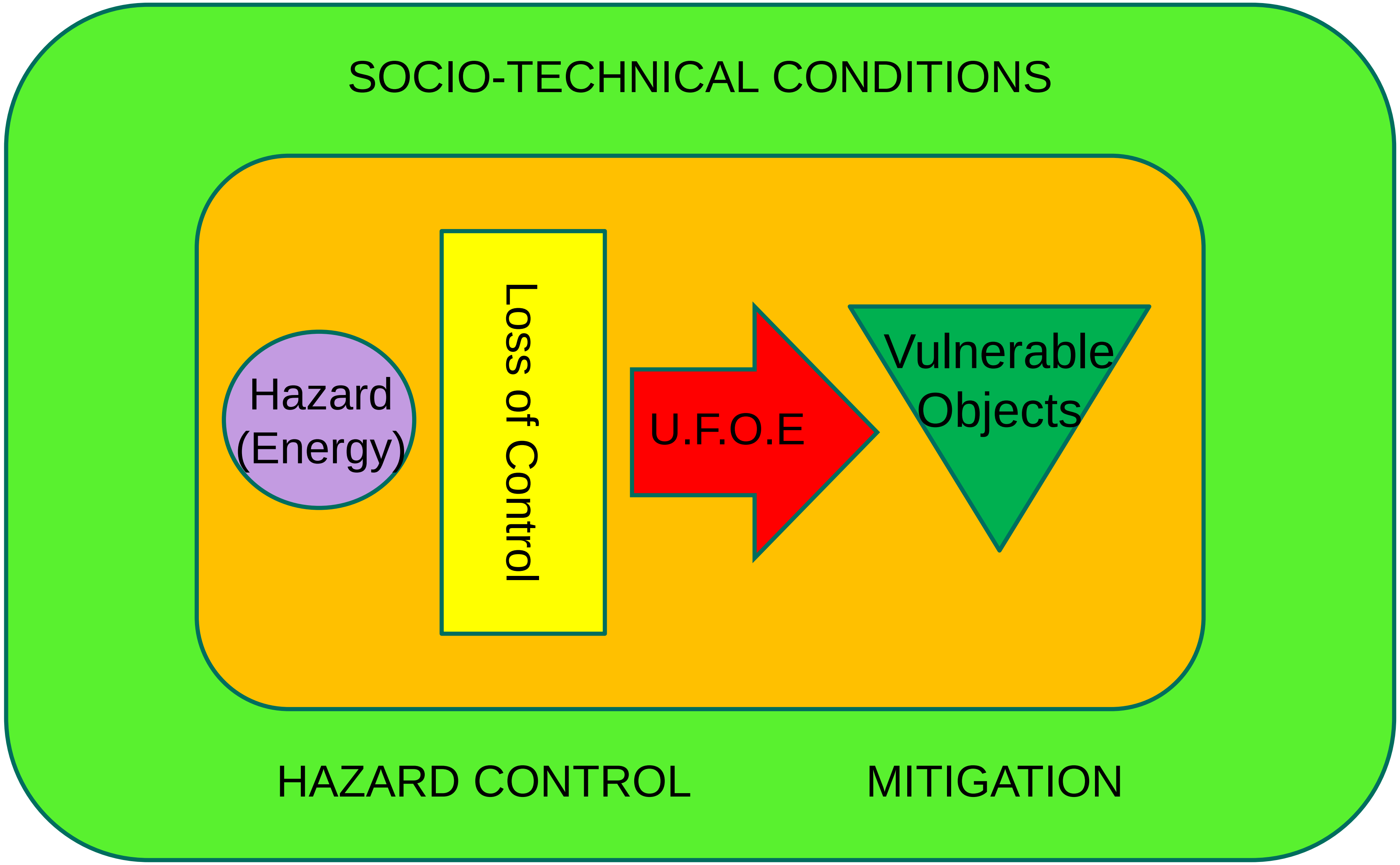
Case Study (H2 Sensor Deployment)



- Qualification test plan and implementation
  - Model 1 and 2 worked in clean and industrial environment
  - Only Model 2 worked in industrial environment
  - Model 2 has now been demonstrated in the field
    - Alternative selection (used by one customer) has failed

General Aspects
Working topics

General accident model

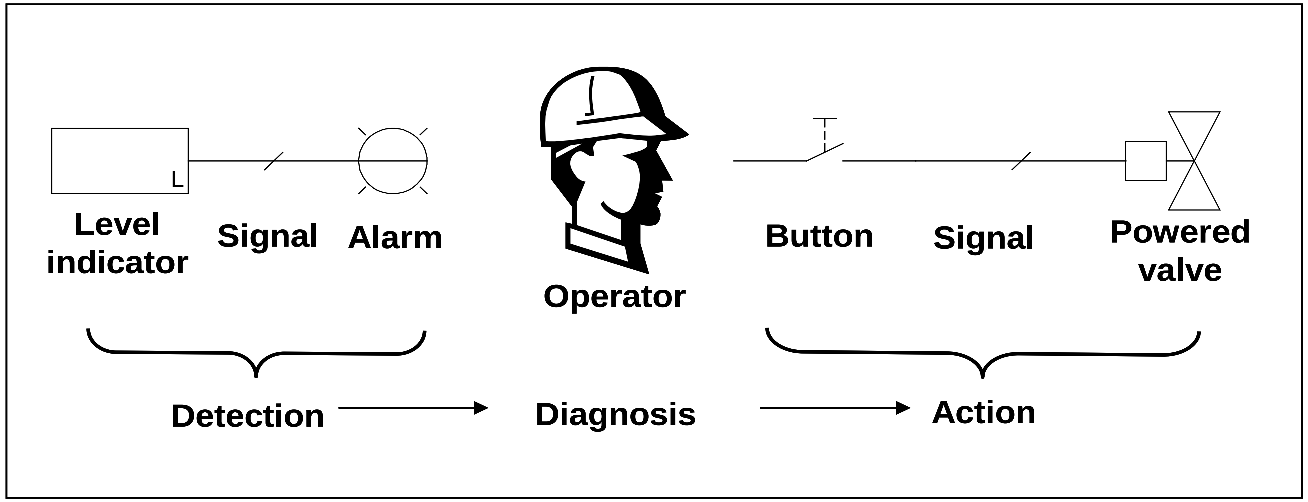


Safety barriers

- Barriers can consist of different elements to perform the barrier function.
- These can be combinations of hardware, software, and actions performed by humans.
- It depends on the type of barrier (or its elements) what management actions are relevant to maintain the barrier's integrity:
  - Human actions require training, commitment, adequate resources
  - Hardware barriers depend on construction, inspection and maintenance.

Complete safety barriers

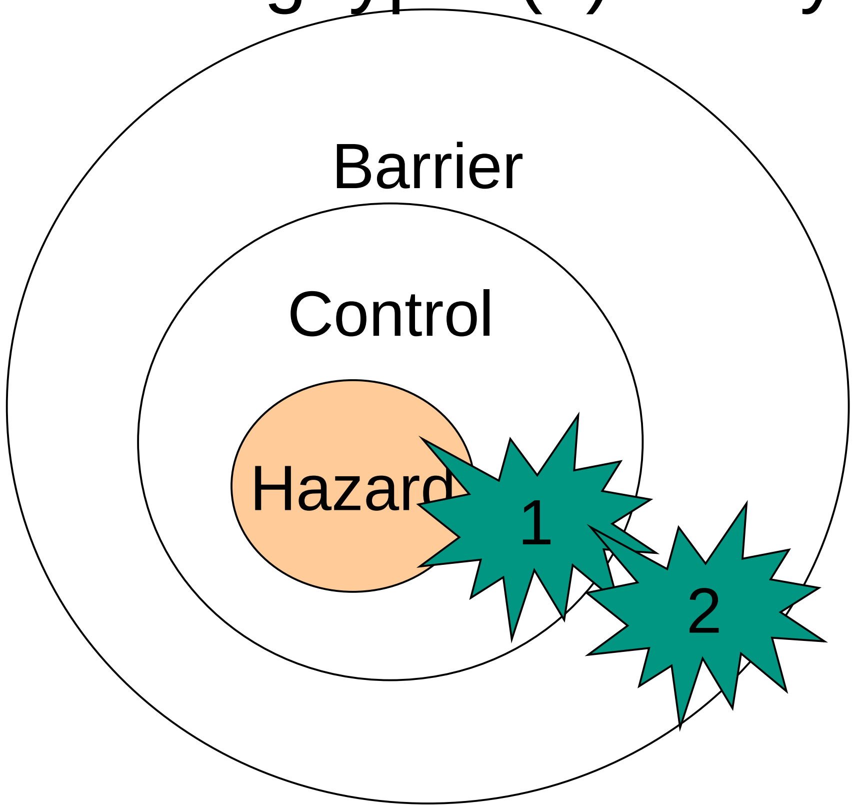
Detect – Diagnose – Act



Safety-critical elements

- (process) control - type (a)
- safety barrier – type (b)

An accident requires first to fail a type-(a) control, then to fail the remaining type–(b) safety barriers”



Consider examples of controls and barriers

General Aspects of Safety- Human behavior

Working topics

- Limited in the field of hydrogen energy:
  - E.g.: Human error assessment of hydrogen refueling technologies; further development of Human Risk Assessment method
  - Studies on perception

  …
- Generic work items may be included
  - Former work in the nuclear field ,
  - work in the field of process industries
    - ARAMIS project: QRA methodology incl. Human and organizational aspects,
    - Norwegian BORA methodologies (off-shore maintenance incl. human error
  - transport safety research (e.g. aviation, maritime)

Human behavior

workers strongly contribute to maintaining safety

- by controlling processes,
- during the design phase
- during the operational phase.

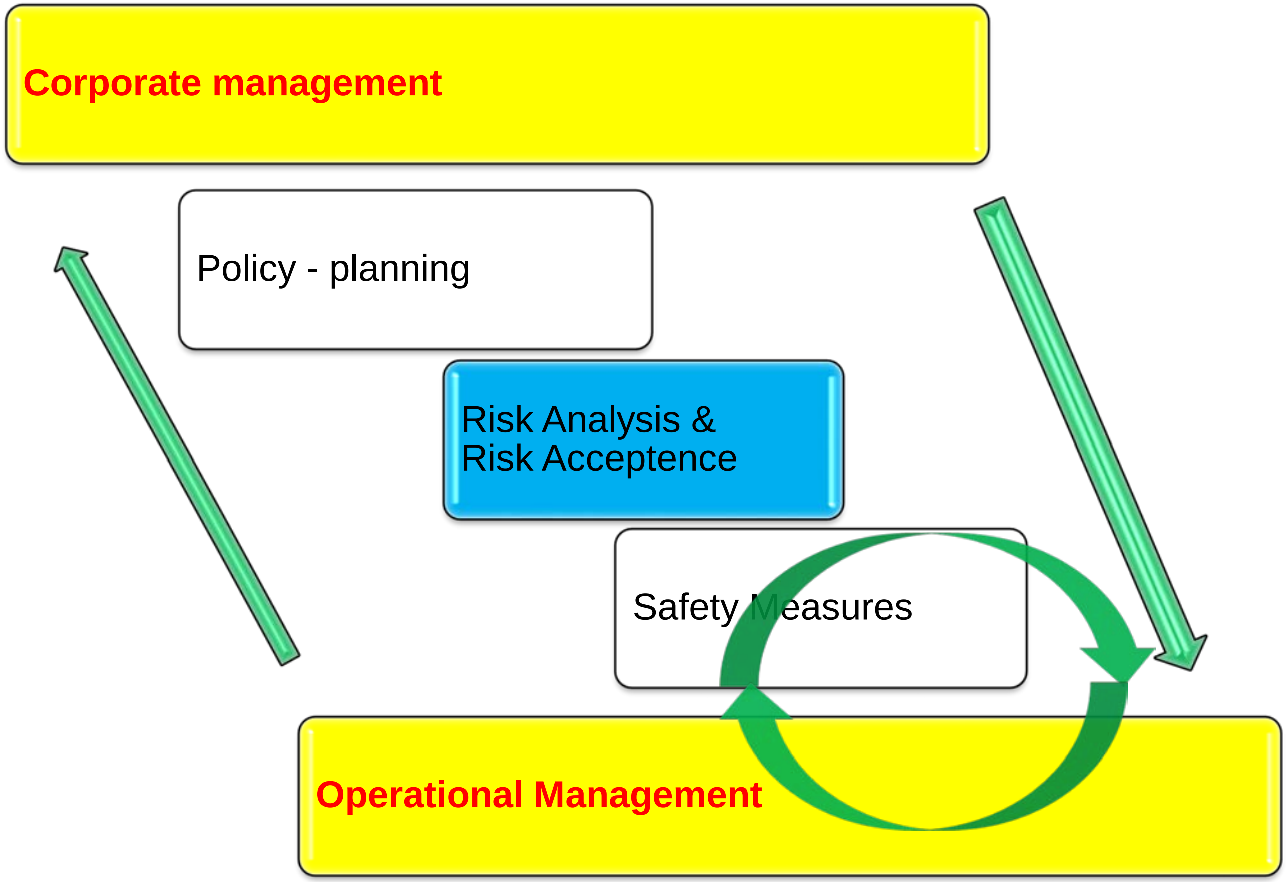
Maintenance and testing phases are especially vulnerable to human error that can seriously influence system safety.

Estimates as to how often human error is the primary causal factor in industrial and transport accidents are in a typically range between 50% and 90%.

Within the H2 Incidents database, human error contributing to particular hydrogen incidents is typically due to one or more of the following factors (Castiglia, Giardina.; IJHE (2013), 38, 1166):

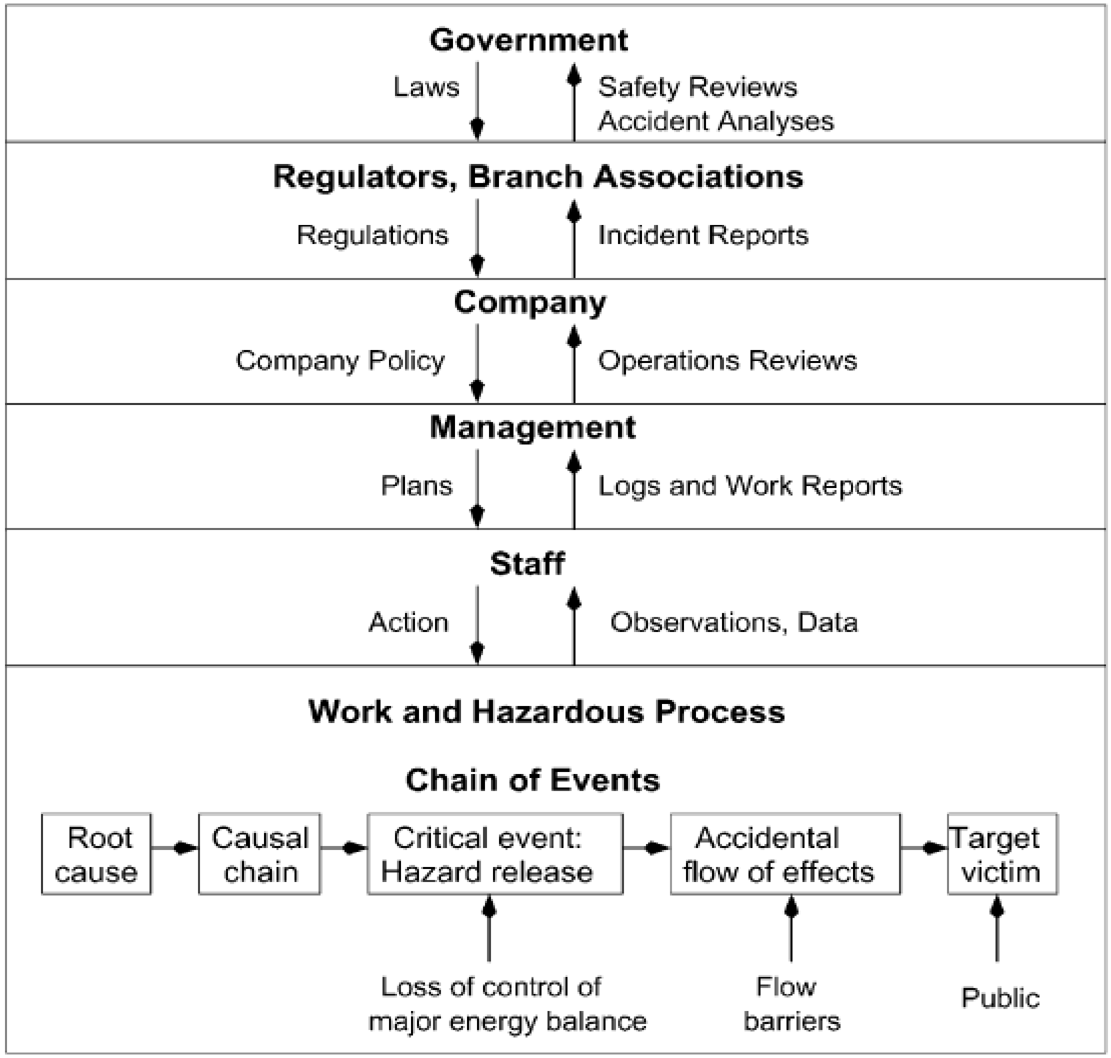
- Lack of personnel training on specific equipment, systems and operating scenarios,
- Inadequately training of personnel regarding the properties of hydrogen and
- the potential consequences of their actions,
- Inattentive and complacent actions by personnel operating
- hydrogen and related equipment, and
- Personnel not following written procedures.
  - Because of personal reasons
  - Because of bad procedures

Management of risk and reliability



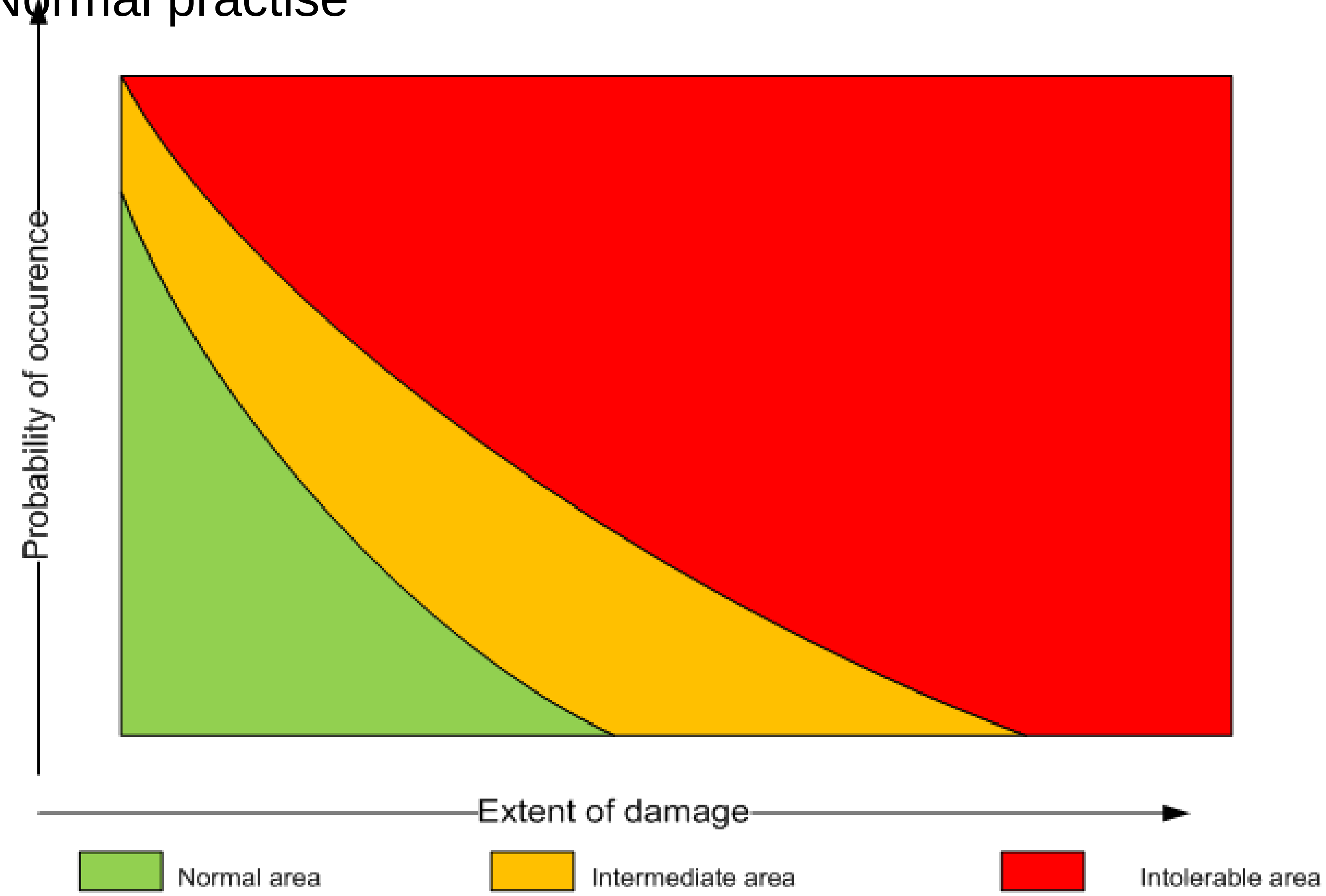
- ***Plan – Do – Check – Act***

Rasmussen and Svedung socio-technical model of system operations



Managing risks and uncertainties

Normal practise



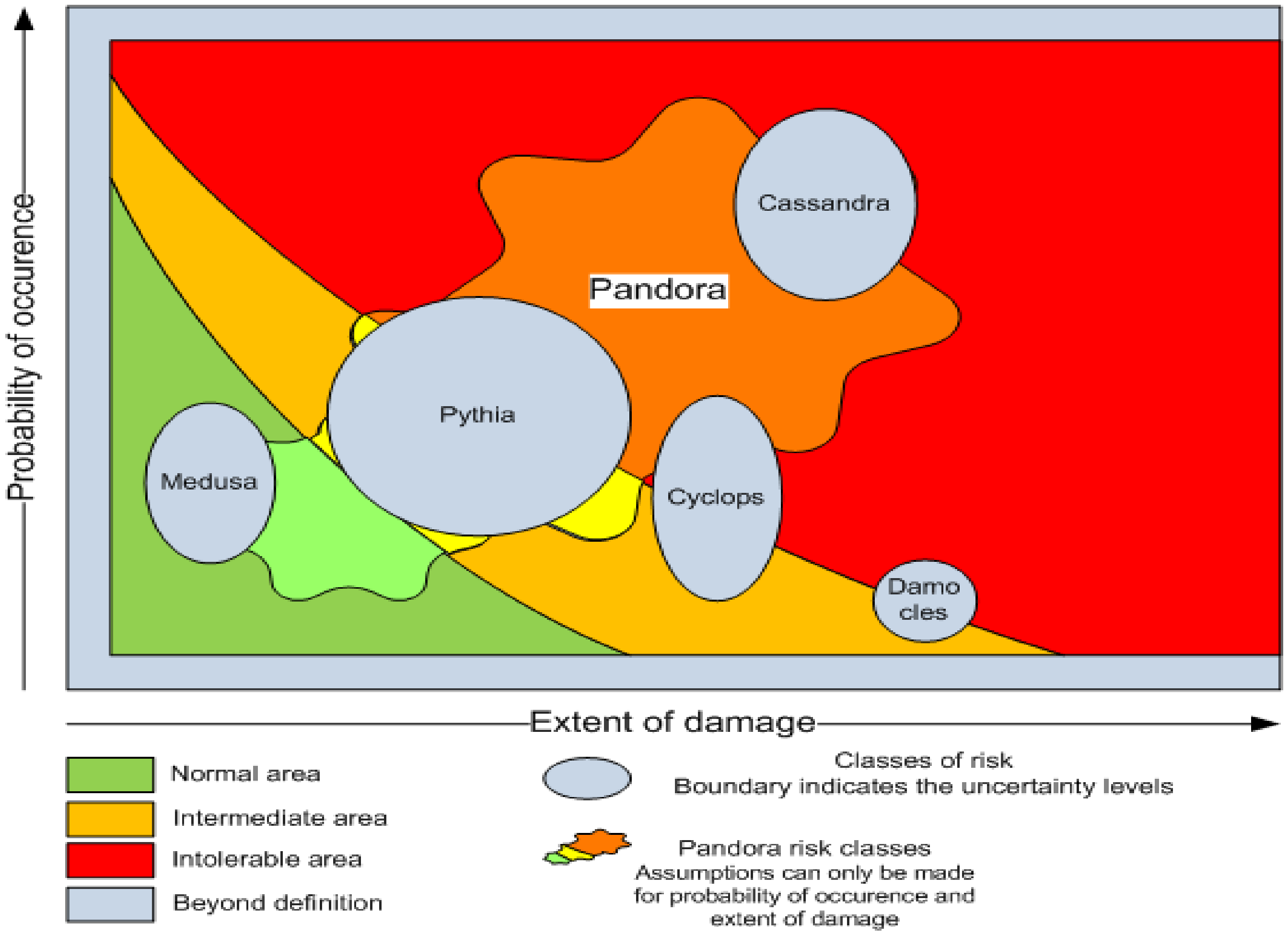
The nature of Uncertainty

Aleatory uncertainty	Epistemic uncertainty
It describes **the inherent variation associated with the physical system or the environment** under consideration.	It derives from some **level of ignorance, or incomplete information** about the system / the surrounding environment.
Other equivalent terms:	
• stochastic uncertainty (variability) • irreducible uncertainty • inherent uncertainty	• subjective uncertainty • reducible uncertainty • model form uncertainty

Real risk assessment problems typically present a mixture of the both types of uncertainty.

Managing risks and uncertainties

Consideration of uncertainties



Redrawn from Renn, Klinke, European Molecular Biology Organization EMBO reports 5 special issue 2004

Management strategies

Management	Risk class	Extent of damage	Probability of occurrence	Strategies for action
Science-based	Damocles Cyclops	High High	Low Uncertain	•Reducing disaster potential •Ascertaining probability •Increasing resilience •Preventing surprises •Emergency management
Precautionary	Pythia Pandora	Uncertain Uncertain	Uncertain Uncertain	•Implementing precautionary principle •Developing substitutes •Improving knowledge •Reduction and containment •Emergency management
Discursive	Cassandra Medusa	High Low	High Low	•Consciousness building •Confidence building •Public participation •Risk communication •Contingency management

Develop a portfolio of hydrogen safety trainings

- Different population e.g. operators vs firefighters
- Different levels e.g. basic firefighters vs. high-rank officers
- Different type of application i.e. stationary vs. transport applications
- Different training duration e.g. 2 days vs. 1 week
- Estimate a cost/trainee for each training
- Promote training through networking channels

"Train European First Responders' trainers and Hazmat Officers"

- **Overall scope**

  Train European First Responder trainers and Hazmat Officer …

  …who will be responsible for establishment of national Hydrogen Safety Training Programs using their own country's language and regulations…

  …based on the educational program and using the operational and virtual reality platforms developed in the frame of HyResponse project.

"Opening" the HyResponse training platform to the hydrogen community

- **Demystification of hydrogen risk**
  - Operators
  - Site managers
  - Firefighters
  - Persons involved in the permitting process
  - Etc.

- **R&D collaboration**
  - Use the operational for R&D activities

Recent Advances in H2 Sensor Performance

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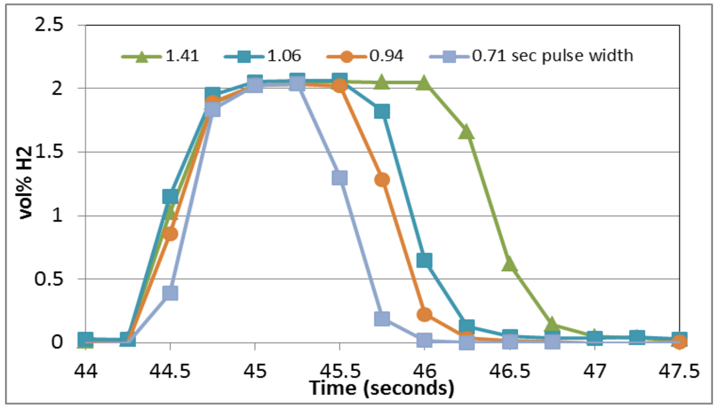
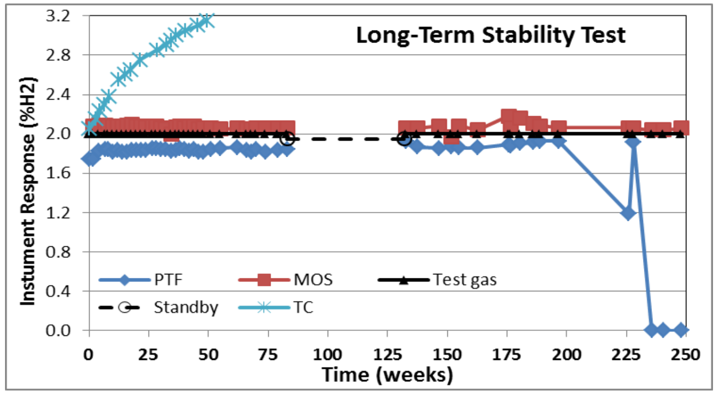
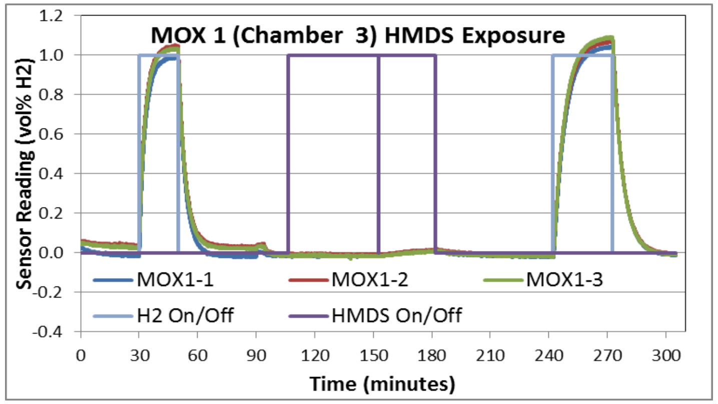
- Fast Sensors are available
  - RT < 1 sec (actual RT ≈ 250 ms)
  - Select models/types (not universal)
- Sensor Lifetime
  - Nearly 5 years (in the lab)
  - Poor performance often manifests early
- Robustness to (some) poisons
  - Based on ISO 26142
  - Some MOX, CGS, TC passed
  - Some MOX, (EC) failed

Table 3.8.2. Targets for Hydrogen Safety Sensor R&D

- Measurement Range: 0.1%-10%
- Operating Temperature: -30 to 80°C
- Response Time: under one second
- Accuracy: 5% of full scale
- Gas environment: ambient air, 10%-98% relative humidity range
- Lifetime: 10 years
- Interference resistant (e.g., hydrocarbons)







Overview of Critical GAPS (Hydrogen Sensors)

Hydrogen Sensors are currently and successfully being deployed to assure safety
- Gap analyses (e.g., H2Sense, feedback) identified critical gaps in performance metrics
- Impact of gaps exist can be exacerbated by specialized applications (e.g., power to gas)

Analytical Metrics

- Long-Term Stability
  - Field Performance
    Long-term impact of T, P, RH, chemical
  - Lack of Predictors
    Mode of failure, ALT, end of life indication
- Selectivity
  Impact on S.R. by varying T, P, RH, Chemical
- Perceived Performance

Operational Metrics

- Calibration and Maintenance

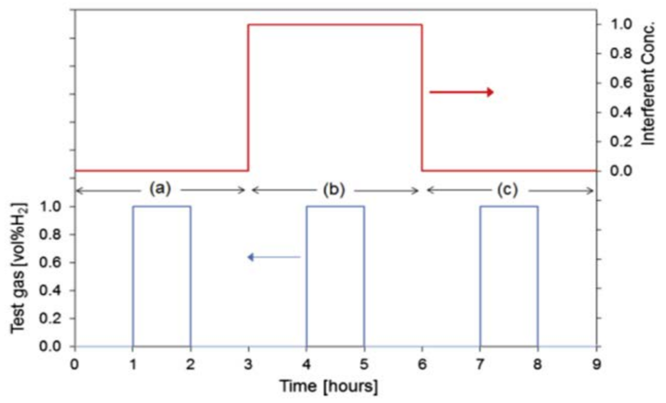
Deployment Metrics

- Sensor Selection and Use
  - Sensor Test Protocols
  - Guidance on deployment/placement
  - Networking vs. WAM
- Certification (costs, harmonization)
- Market Sustainability

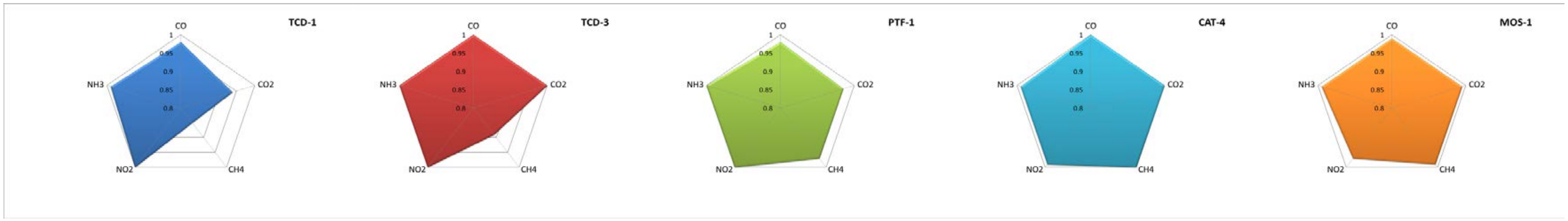
Specialized Applications

- Power to Gas
- C&S support
  Pre-normative research, verification technology

Sensor Selectivity
Impact of chemical interferents



- Tests performed have shown a good behaviour of sensors against contaminants/poisoning
- Test protocol according to ISO 26142
- Relevant to code and standard development



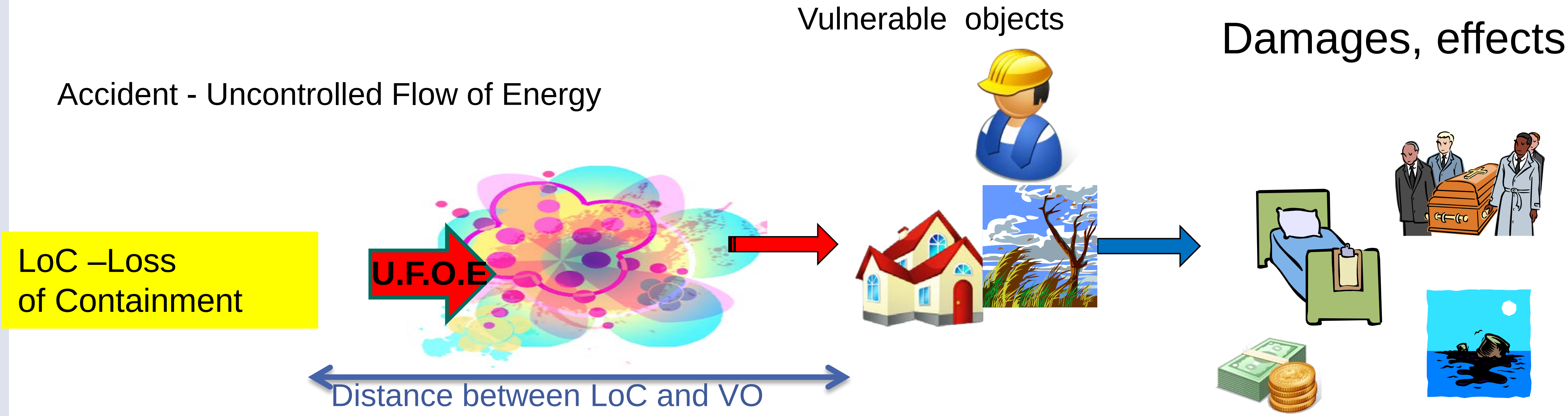
Sensors in real environment are showing a worse behaviour → Is ISO 26142 test protocol adequate?

Possible improvements in test protocol

- Longer exposure time
- Higher contaminants/poisoning concentrations
- More real environmental conditions (air with RH)
- Expanded list for other applications (e.g. automotive vs. infrastructure)

General Aspects
New gaps or directions

New gaps or directions



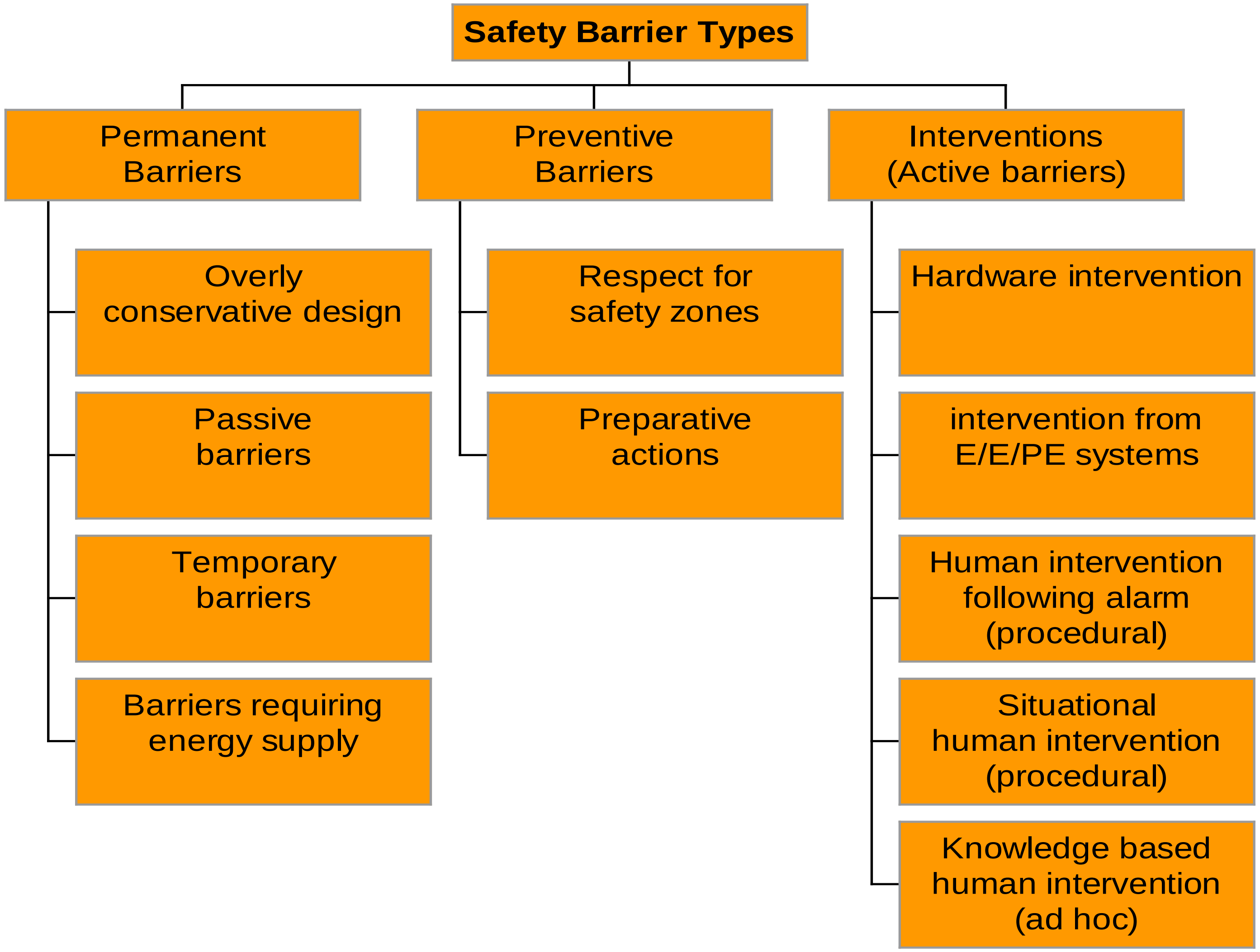
Monte Carlo methods using simplified models for prediction:

- What are the worst case damages?
- What are the most likely damages?
- How much time is there for escape or evacuation ?
- What emergency planning and responce is necessary ?

General Aspects
New gaps or directions

- Adressing safety barrier types and their PFD changes by human behavior

PFD = probability of failure on demand



General Aspects of Safety - Training
New gaps or directions

"Train European First Responders' trainers and Hazmat Officers"

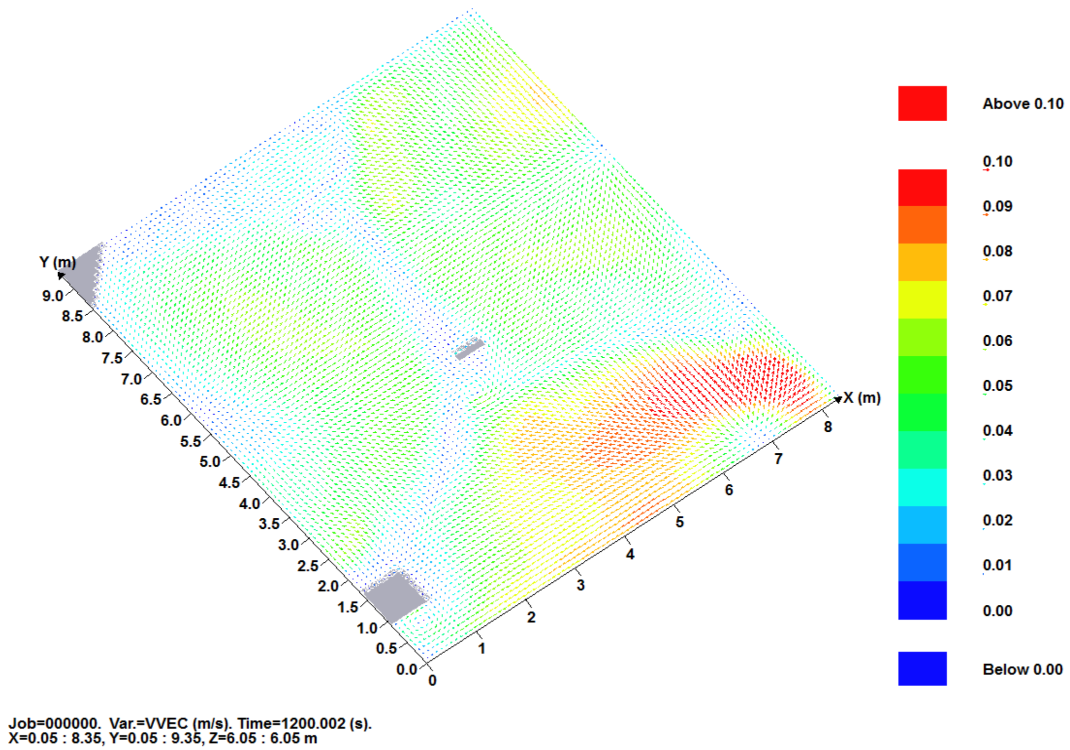
Overall scope:

Train European First Responder trainers and Hazmat Officer …

- who will be responsible for establishment of national Hydrogen Safety Training Programs using their own country's language and regulations…
- based on the educational program and using the operational and virtual reality platforms developed in the frame of HyResponse project.

Research Directions:
Guidance on Sensor Placement
Integrated Empirical and Theoretical Modeling of H2 Releases

- Experts Team
  - NREL (C. Rivkin, W. Buttner)
  - JRC (E. Weidner, D. Melideo)
  - AVT (A. Tchouvelev)
- Project Overview
  - Small indoor facility (initial focus)
  - Combined empirical/theoretical
  - Develop Guidance Document (NFPA 2)
- Future
  - Guidance over larger area,
  - Minimize the number/placement of sensors ***without*** compromising safety *(A stochastic programming approach for gas detector placement using CFD-based dispersion simulations,* S.W. Legg, et al. Computers and Chemical Engineering 47 (2012) 194– 201)



A.V. Tchouvelev, "Installation Requirements for Hydrogen Isotope Laboratory", Report to Atomic Energy of Canada Limited, February 2014.

Long-term stability
accelerated stability testing

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On-board vehicle sensor requirements
- 10 year life with no maintenance
- Low cost

Stability Testing
- Chemical stress tests
  - interferents/poisons
- Physical stress tests
  - Thermal Shock (-45 ºC to +85ºC cycling
  - Harsh Conditions (T to 60ºC, 90% RH)
  - High Temperature (90º)
  - Low Temperature (-40ºC)
- Under development
  - Efficacy is to be demonstrated

SAE INTERNATIONAL

SURFACE VEHICLE TECHNICAL INFORMATION REPORT (TIR)	J3089	PropDft 2015
	Issued	xxxx-xx
Characterization of On-board Vehicular Hydrogen Sensors		

RATIONALE

Standards (such as SAE J2578, SAE J2579, and ISO 23273) and regulations such as the Global Technical Regulation Number 13 (GTR)[1] provide requirements for hydrogen and fuel cell vehicles and associated hydrogen systems. While these standards and regulations do not explicitly prescribe that hydrogen sensors are to be used on-board the vehicle, vehicle manufacturers and system integrators may chose to use hydrogen sensors as part of their process control and fault management strategies to protect occupants of the vehicle and by-standers from flammable gas hazards.

This SAE report decribes test protocols and defines tests that can be employed by system integrators and vehicle manufacturers and their suppliers to evaluate the performance of hydrogen sensors under conditions likely to exist within their systems/vehicles. By so doing, the proper sensor can be selected for on-board their vehicles.

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[1] "Global technical regulation on hydrogen and fuel cell vehicles", ECE Trans, 180, Addendum 13 (July 19, 2013).

Proposed "Long-Term Stability" Tests
(based on qualification standards for other components)
Under Development

TIR SAE J3089 (guidance document)
for characterization of on-board H2 Sensors

SUMMARY for Sensor GAPS Research Priorities

What we are addressing (ongoing)

Long-Term Stability

- Field Performance Testing
- Laboratory Poison Study

Selectivity Testing

- On-going study (chemical and environment

Sensor Test Protocols

- Developing new faster methods

Perceived Performance

- Outreach and case studies

Guidance on deployment/placement

- Integrated modelling/empirical assessment

Specialized Applications

- Power to Gas
- Pre-normative research (LH2 profiling)
- Verification tools for GTR 13

What we proposed to address

Long-Term Stability

- Predictors (ALT/Stress Test)

Calibration and Maintenance

- "AutoCal"

What we are/can not address

Long Term Stability

- Mode of Failure, End of life indication,
- Validated ALT
- Some Physical Stress Testing

Certification (costs, harmonization)

- Can guide but not impose requirements

Market Sustainability

A Plug—Book on hydrogen sensors

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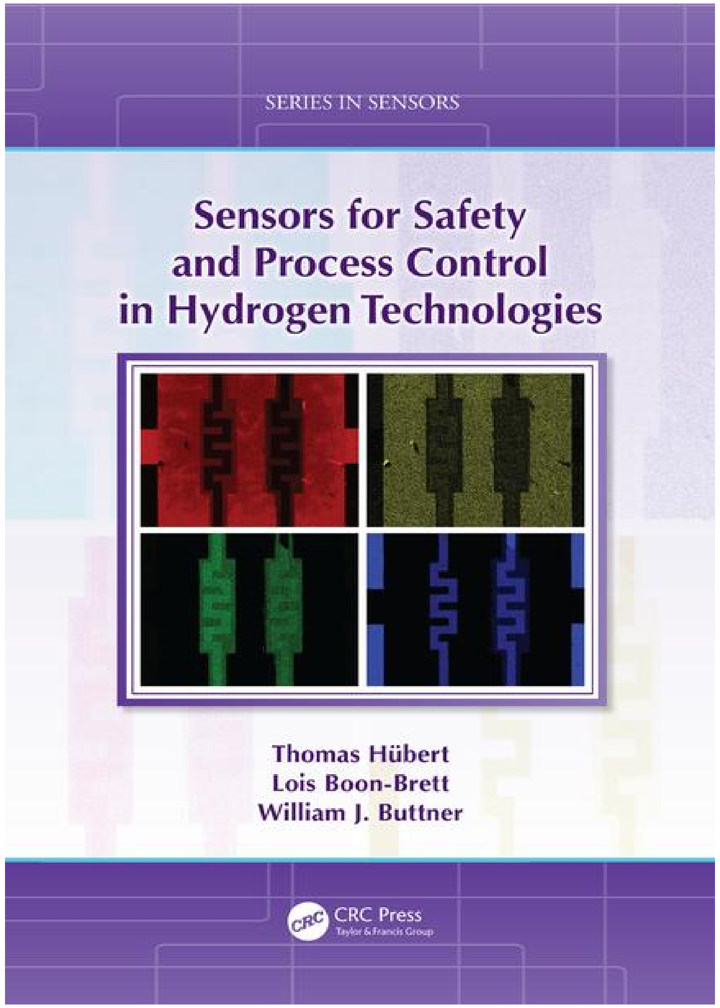
CRC Press Series in Sensors

- Published in December 2015!
- International Team of experts and friends!
  - Lois Brett, Scientific Officer/JRC, Lead Scientist (former) of the JRC Sensor Laboratory
  - Thomas Hűbert, Lead Scientist of the BAM Sensor Laboratory
  - **Eveline Weidner, Scientific Officer/JRC, Lead Scientist of the JRC Sensor Laboratory**



European Commission

BAM
Bundesanstalt für Materialforschung und -prüfung

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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