THE STRONGEST LINK.

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# HYDROGEN TECHNOLOGIES - SOME CHALLENGES AND OPPORTUNITIES FOR THE INDUSTRY

**Prof. Dr. Thorsten Arnhold – R. STAHL AG Germany**


"water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable"
Jules Verne in The Mysterious Island
HYDROGEN
ENERGY
STORAGE
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09. Februiary 2021

# World's first 'hydrogen law' takes effect. What's in it?

To usher in the hydrogen economy, South Korea passed the world's first hydrogen law.  It centers on the development of an ecosystem for a hydrogen economy and expanded public access to the alternative fuel.....

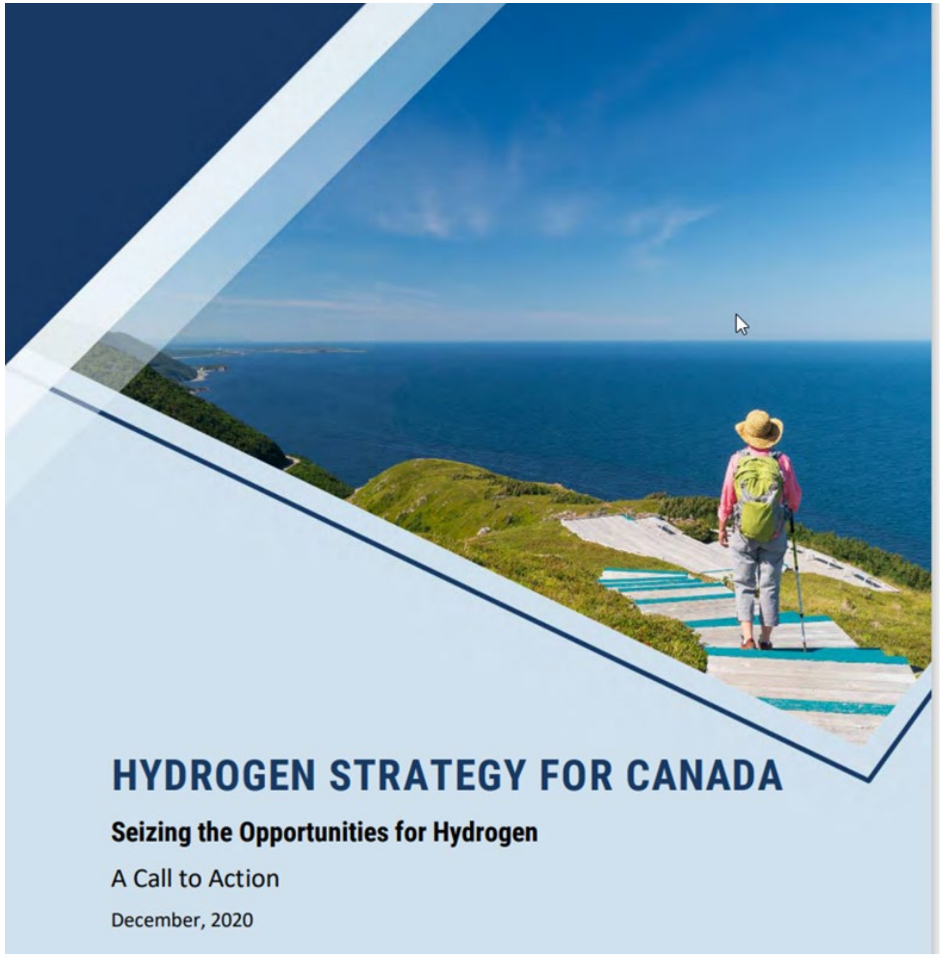

….Most importantly, the hydrogen law tackles the **safety issues that had long remained in a regulatory blind spot**. Previously, hydrogen equipment – electrolyzers, portable fuel cells and hydrogen extractors – and fuel cell facilities that directly used hydrogen weren't subject to periodic government safety checks. **Now, safety assurance will be carried out in three steps -- technological safety at the design stage, an on-site examination upon completion of a facility, and annual safety checks….**

# CANADIAN H2 STRATEGY: AWARENESS FOR SAFETY ISSUES IS CURRENTLY LACKING

## AWARENESS

There is currently a lack of awareness about the opportunities for hydrogen and around safety issues, both by the public, as well as within industry and government.

Limited domestic hydrogen deployments have further resulted in a lack of tangible case studies to increase awareness and support long-term planning and buildout. For example, mine safety and reliability must be successfully proven in the pilot stage before technology can be fully adopted.



# THERE ARE MANY MISUNDERSTANDINGS IN THE MARKETS...

**ABC Inc.**

Home Products Development Career Company

## 10 important questions about hydrogen

01 | What is hydrogen? +

02 | How does the energy density of hydrogen compare to conventional fuels? +

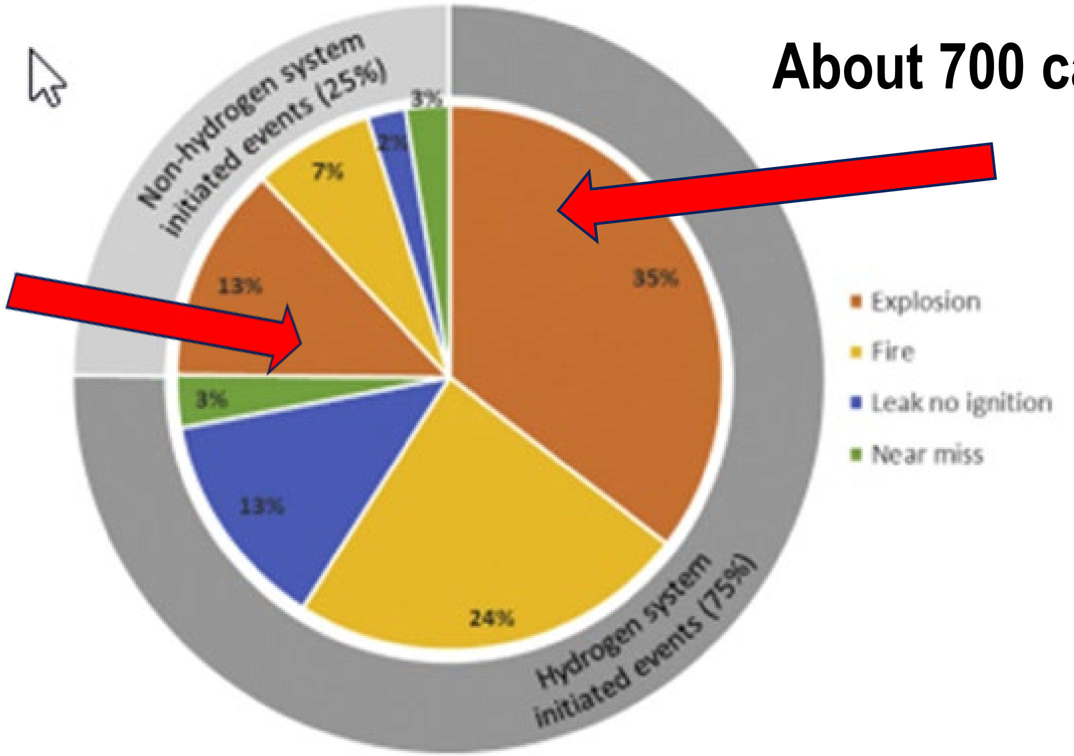
03 | How dangerous is the use of hydrogen? +

04 | Is hydrogen explosive? −

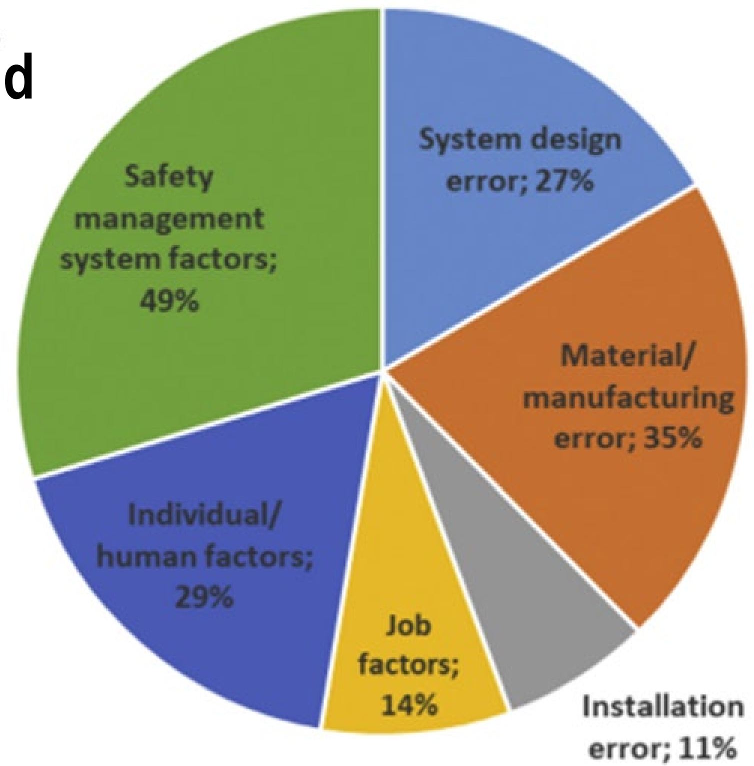
No. Hydrogen-air mixture is combustible, but does not explode. A mixture of hydrogen and pure oxygen (oxyhydrogen) is explosive.

# HIAD 2.0 EUROPEAN HYDROGEN INCIDENT AND ACCIDENT DATABASE @ 2022 EUROPEAN HYDROGEN SAFETY PANEL (EHSP)

About 700 cases found



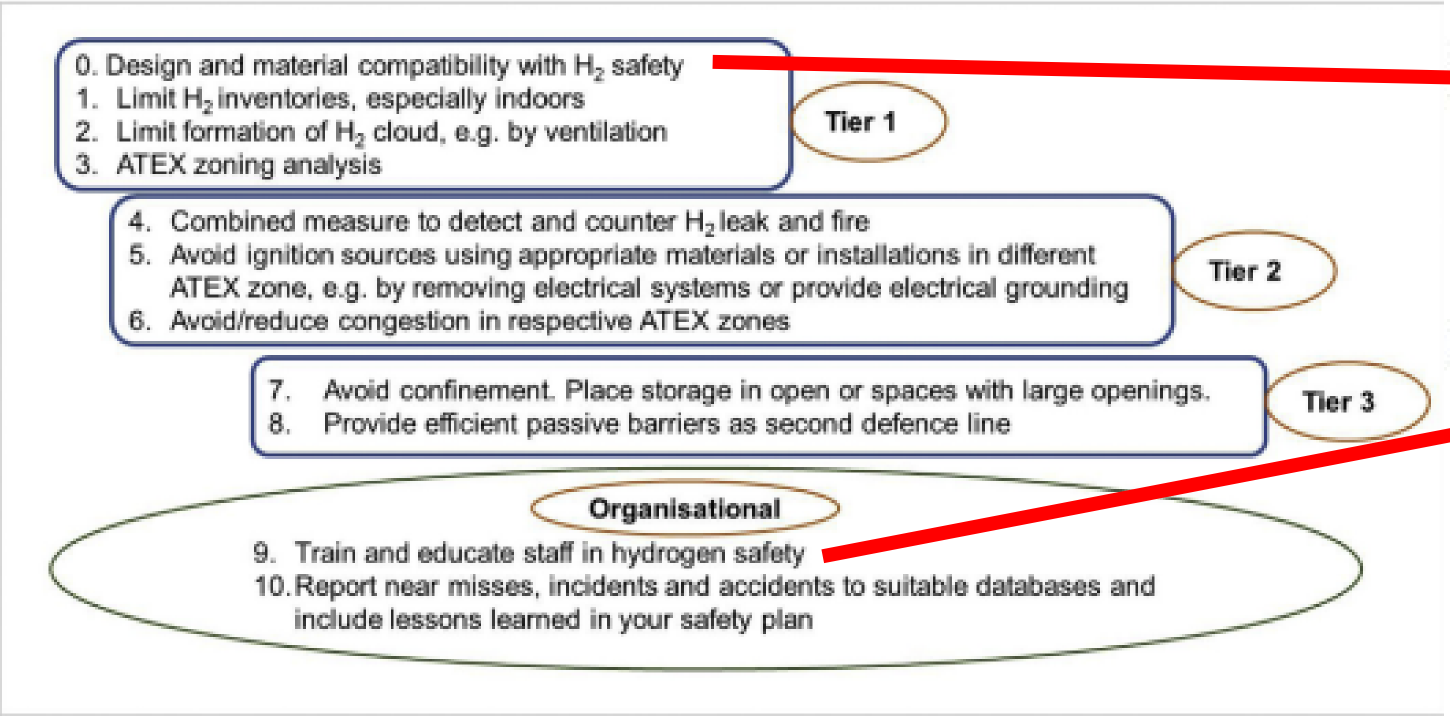

Percentages of the events initiated by hydrogen or non-hydrogen systems (outer circle) and those related to different consequences (the inner circle)



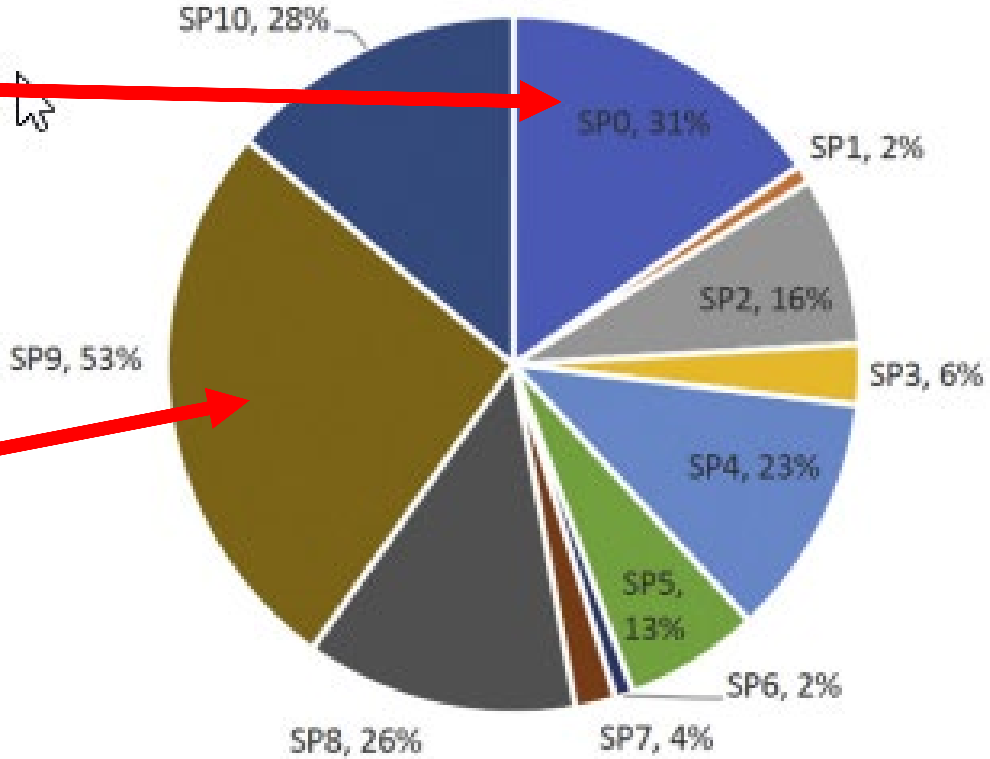

Percentages related to the causes of the events considering multiple causes per event

We., J. X. et al: Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database; International Journal of Hydrogen Energy 47(2022)

# HIAD 2.0 EUROPEAN HYDROGEN INCIDENT AND ACCIDENT DATABASE @ 2022 EUROPEAN HYDROGEN SAFETY PANEL (EHSP)




Hydrogen safety principles (SP#) (European Hydrogen Safety Panel, 2021).



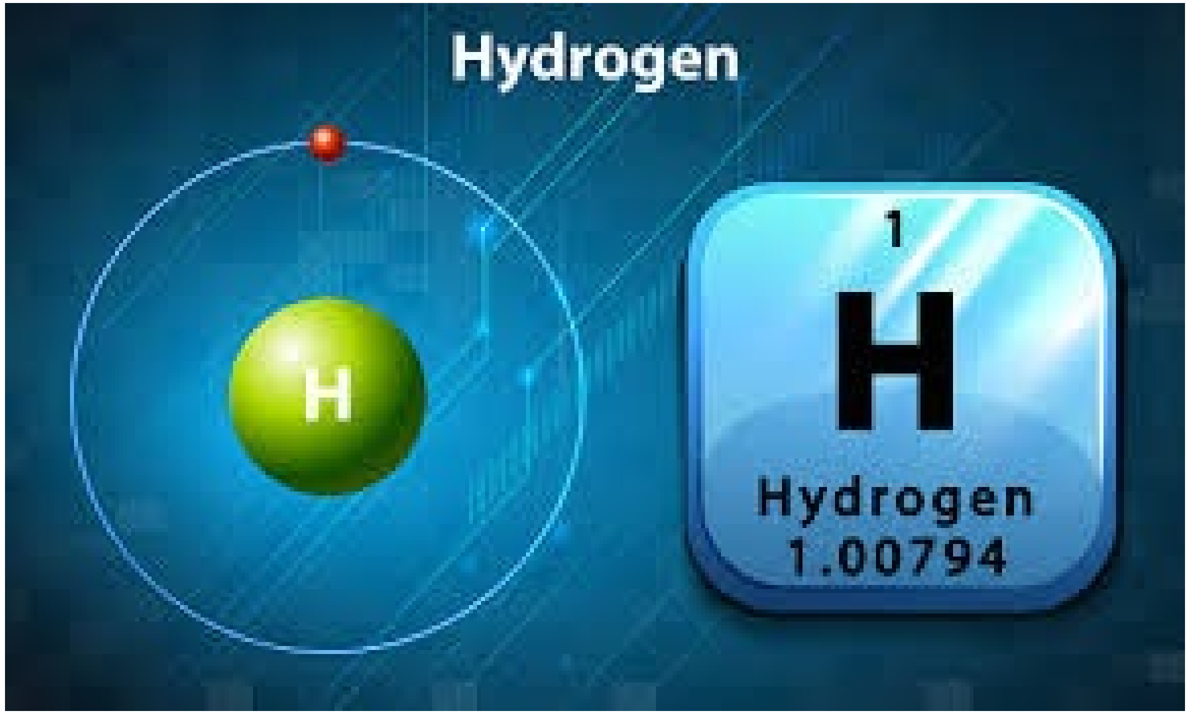

Percentages of events related to the 11 Safety Principles (SP#)

We., J. X. et al: Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database; International Journal of Hydrogen Energy 47(2022)

# SOME HYDROGEN SPECIFIC INFORMATION

# TECHNICAL REPORT ISO/TR 15916: 2015

- Overview of hydrogen applications
- Basic properties of hydrogen
- Safety considerations for the use of gaseous and liquid hydrogen
- Team approach and education/training needed for the safe use of hydrogen
- Mitigation and control of hazards and risks
  - Deflagration and detonation
  - Oxygen enrichment
  - Gas detection (ISO 26142); fire detection
  - Many other aspects



# CANADIAN HYDROGEN INSTALLATION CODE – 4.3.1 BASIC SAFETY REQUIREMENTS

When performing the installation or

maintenance work, the installer **shall** take

into account the guidelines provided

In the document ISO/TR 15916.

# IMPORTANT US REGULATIONS REGARDING HYDROGEN SAFETY

ANSI/AIAA G-095A-2017
(Revision of AIAA G-095-2004)

**Guide**

American National Standard

**Guide to Safety of Hydrogen and Hydrogen Systems**



AIAA

**SANDIA REPORT**
SAND2021-2955
Printed March 2021

Sandia National Laboratories

**Federal Oversight of Hydrogen Systems**

Austin R. Baird, Brian D. Ehrhart, Austin M. Glover, Chris B. LaFleur

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

**This report contains an overview of the regulations that apply to hydrogen**

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

**Hydrogen Technologies Safety Guide**

C. Rivkin, R. Burgess, and W. Buttner
*National Renewable Energy Laboratory*

**National laboratory of the U.S. Department of Energy**

**NREL is a national laboratory of the U.S. Department of Energy**
**Office of Energy Efficiency & Renewable Energy**
**Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

**Technical Report**
NREL/TP-5400-60948
January 2015

Contract No. DE-AC36-08GO28308

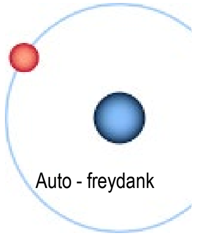
# KEY CHARACTERISTICS OF GASEOUS HYDROGEN

Hydrogen is flammable, non-toxic and non-corrosive. It is colorless, insipid and odorless. It can suffocate people.

| | Hydrogen (H2) | Methane (CH4) |
|---|---|---|
| Density [kg/m$^3$] | 0.08388 | 0.7175 |
| Molecule size [nm] | 0.276/0.106* | 0.324 |
| Ignition temperature in air [°C] | 585 | 540 |
| Diffusion coefficient cm$^2$/s in atm air | 0.768 | 0.215 |
| Max. flame speed [cm/s] | 346 | 43 |
| Ignition range in air [vol%] | 4 to 73 | 5 to 14 |
| Heat conductivity [W/(m x K)] | 0.18339 | 0.0341 |
| Minimum ignition energy [mJ] | 0.02 | 0.28 |

*ionised

Weka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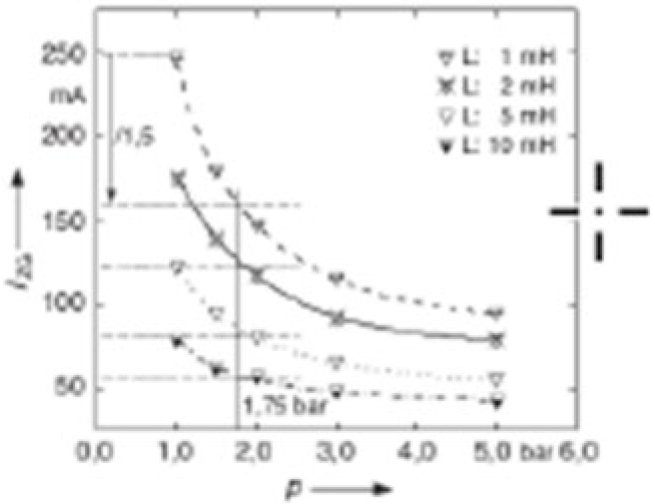


BAM

Zündstrom für ein Wasserstoff-Luft-Gemisch (Verh. 21/79) in Abh. vom Druck

E. Brandes; M. Thedens: Kenngrößen des Explosionsschutzes bei nichtatmosphärischen Bedingungen PTB Mitteilungen 2003

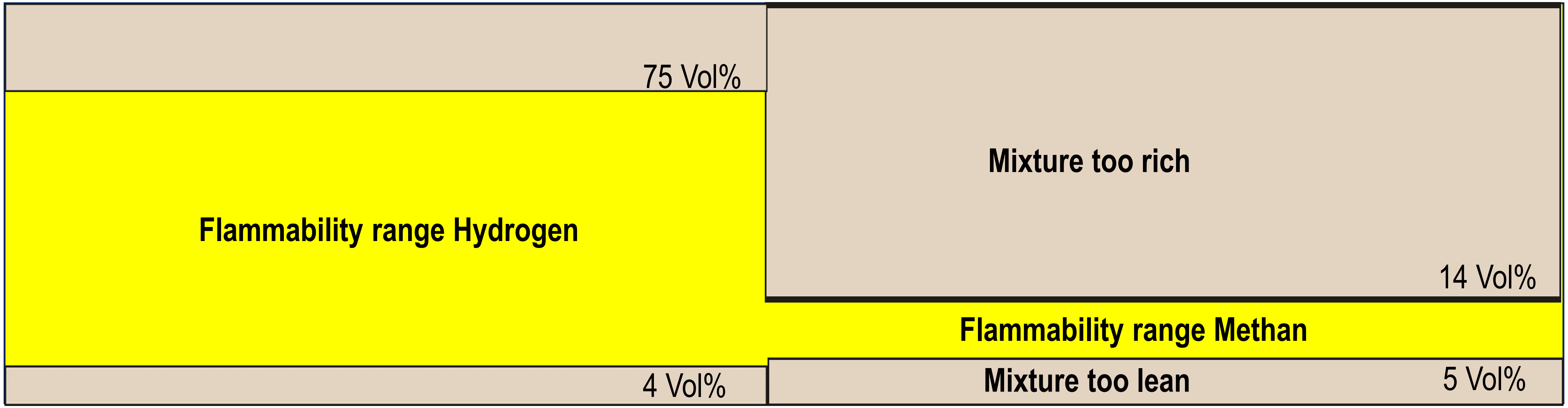
mdr

# HYDROGEN IS 14 TIMES LIGHTER THAN AIR!

- Outdoors, the extremely low density allows released hydrogen to escape quickly into the atmosphere.
- If there are obstacles in the way (e.g. covers or roofs) or if it is released in rooms, the extremely high buoyancy of the hydrogen creates very large concentration differences between the exit point and the area under the ceiling in a very short time.
- The turbulence that arises in the hydrogen flow can easily lead to detonation transitions.

WorldPress

# EXTREMELY BROAD FLAMMABILITY RANGE !



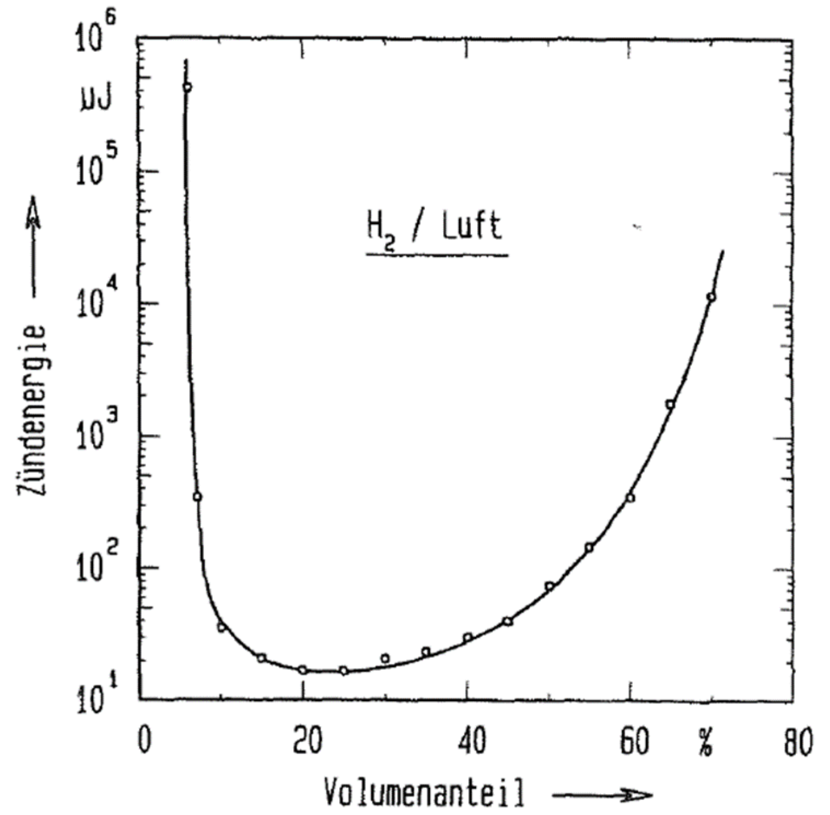

## Pressure dependence of the hydrogen explosion limits

The behavior of the UEL is in comparison with other fuels atypical!

| Pressure / bar | 1 | 10 | 100 |
|---|---|---|---|
| LEL in Vol-% | 4,3 | 4,9 | 5,8 |
| UEL in Vol% | 78,5 | 72,4 | 74 |

# MINIMUM IGNITION ENERGY

The ignition energy is extremely low over a relatively wide concentration range of 10…50%: below $10^2$ µJ




Source: Reichelt Chemietechnik; Explosion protection manual

# VISCOSITY

- Viscosity is the internal resistance of a fluid to shear stress.
- Due to its small molecule size, hydrogen has a very low viscosity.
- **As a result, the flow rate is relatively high if the gas escapes through leaking (porous) areas of seals, conduits, etc.**
- GRAHAM effusion law
  - Average molar mass of air: 29 kg/kmol
  - Average molar mass of H2: 2 kg/kmol
  - Average molar mass of $CH_4$ 16 kg/kMol
- **Airtight does not mean hydrogen-tight!**

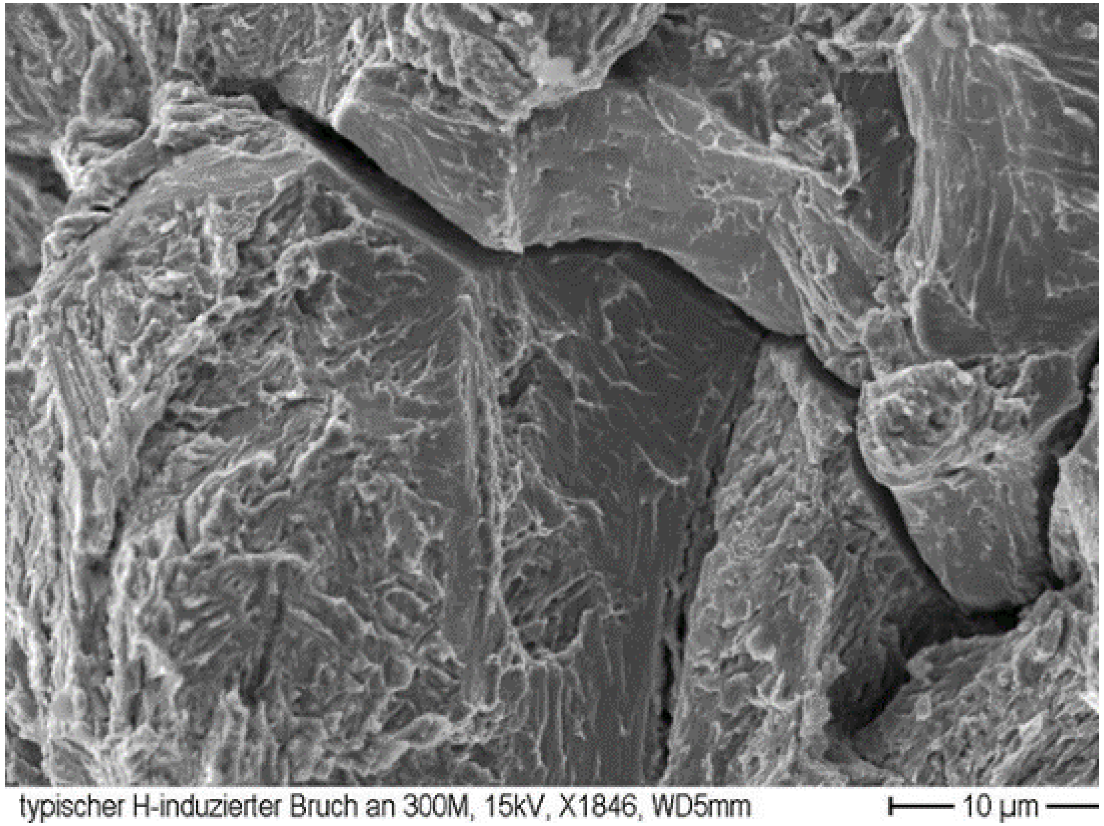
**Grahams Effusion law**

$$\frac{v_1}{v_2} = \sqrt{M_2/M_1}$$

$$v_{H2} = 3{,}8 \cdot v_{Air}$$

Source: HAZ/TU Clausthal Regenerative Energiequellen WS 2007/2008

# HYDROGEN EMBRITTLEMENT



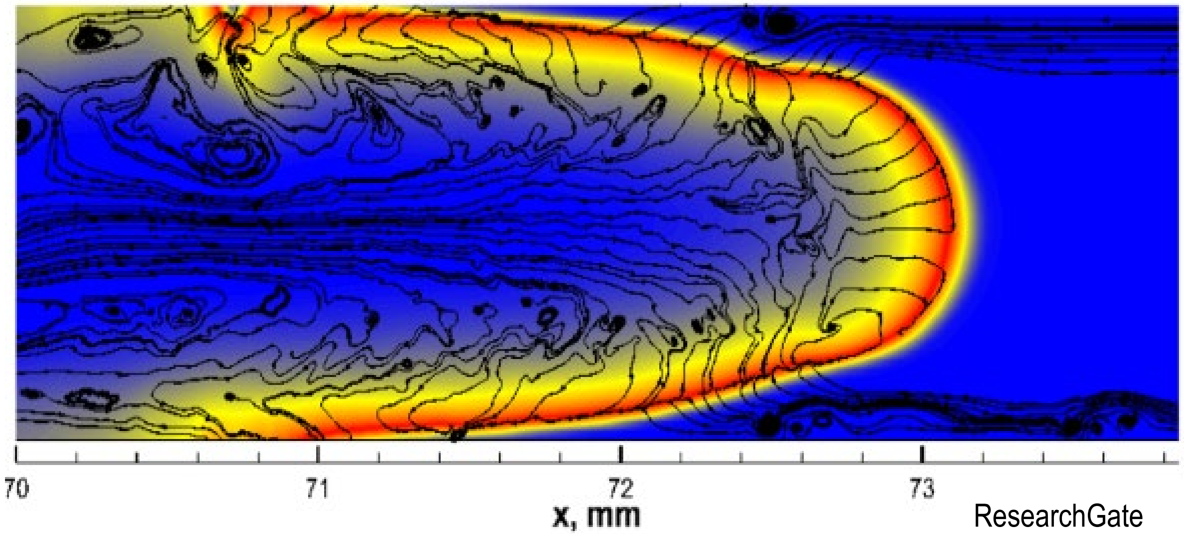

VauQuadrat

Steinbeis

# COMBUSTION SPEED:
# LAMINARE BURNING VELOCITY

| Fuel | $V_{flame}$ in cms-[1] nach 1) | $V_{flame}$ in $cms^{-1}$ nach 2) |
|---|---|---|
| Acetylen | 173 | 155 |
| Methan | 36,4 | 44,8 |
| Wasserstoff | 320 | 325 |

Laminar burning velocity: movement of the flame front in a homogeneous gas-air mixture per unit of time perpendicular to the flame front in the unburned mixture.



ResearchGate


1) Mannan S. (2005) Lees`loss prevention…3. Auflage Elsivier, Amsterdam
2) Center for chemical process safety (1994) Guidelines for evaluating the characteristics of vapour cloud explosions…American Institute of Chemical Engineers, New York

# TECHNICAL RISKS WHEN HANDLING HYDROGEN

**…result from**:

the physical and chemical properties of hydrogen

the influence of hydrogen on the material properties

the uncontrolled release in accident situations (pressure)

the low temperatures of liquid hydrogen

# HYDROGEN EXPLOSIONS

# DEFLAGRATION AND DETONANTIONS

# RESULTING HAZARDS

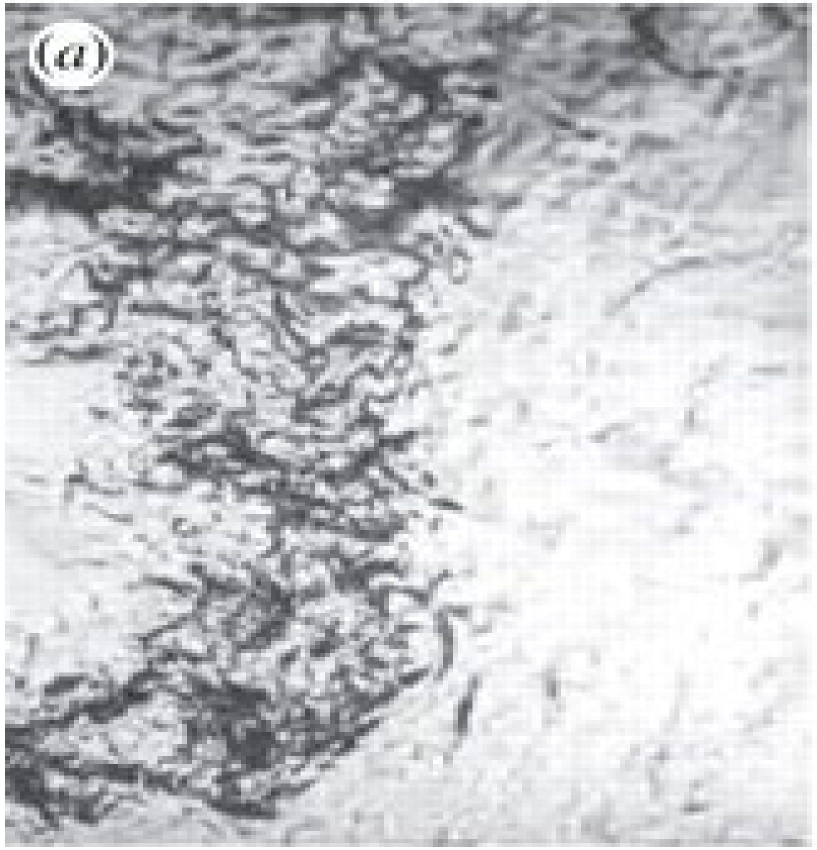
# HYDROGEN EXPLOSIONS: OXYHYDROGEN, THE CLASSIC

- Oxyhydrogen: $2H_2 + O_2 \rightarrow 2H_2O$
- Mixture of hydrogen and pure oxygen in which the ratio is exactly 2:1.

Dennios.at

# HYDROGEN DEFLAGRATION AND DETONATION

- Expansion due to diffusion of heat and radicals
- Combustion speed of hydrogen is between 2 and 3 m/s, therefore 10 times higher than that of hydrocarbons!
- The visible spread (flame speed) is even higher due to the additional force from hot combustion products
- Blockages in the direction in which the flames spread can significantly increase the pressure and flame speed (8 to 10 bar)
- The upper limiting value is the speed of sound in a stoichiometric H2/air mixture




Geraint Thomas: Some observations on the initiation and onset of detonations; The Royal Society publication 2012

# DEFLAGRATION TO DETONATION TRANSITION (DDT)

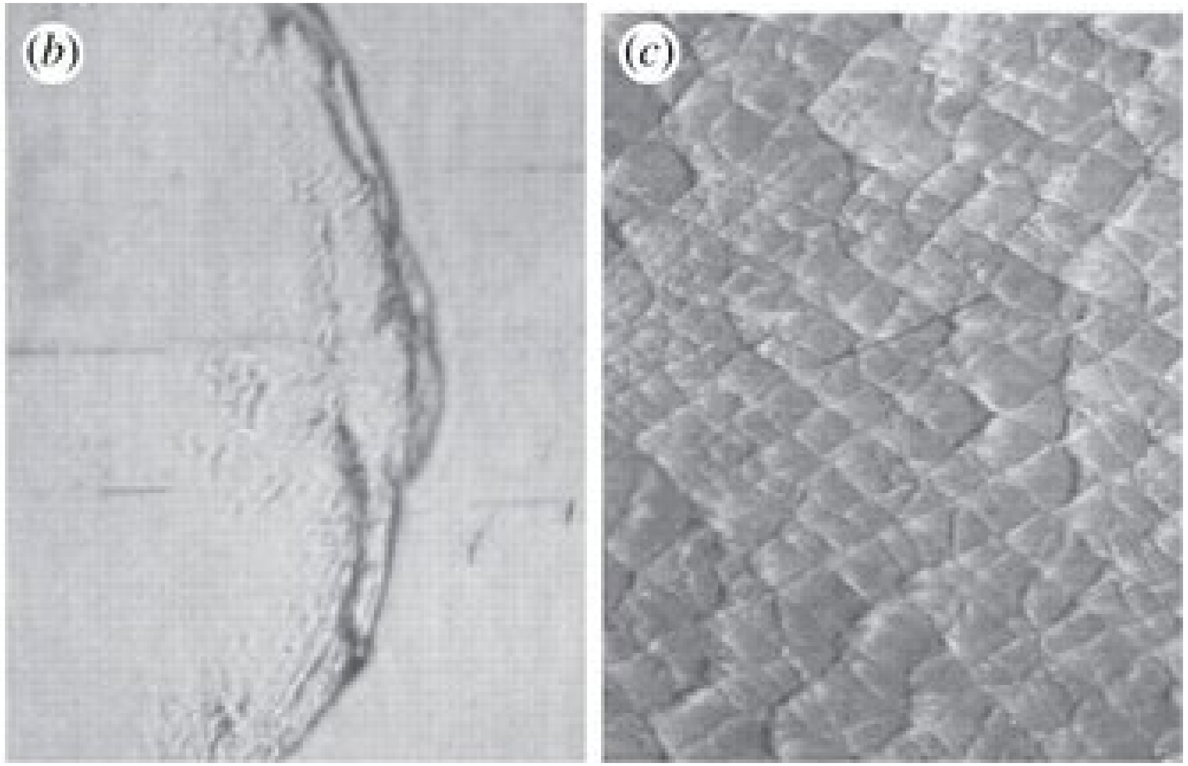
- Reason: closed rooms and obstacles in the way the flame spreads
- Pipes, containers, walls can significantly increase the flame speed
- Above a certain speed, turbulence and instability occur, which ultimately leads to detonations.

FIG. 7.19 Garage and vehicle damage from 12% cluttered detonation.

Brun, K.; Allison, T. C.Machinery and Energy Systems for the Hydrogen Economy

# DETONATION OF HYDROGEN

- Spread due to adiabatic heating due to shock waves
- Caused by significant pressure increase in uncombusted mixture and/or very high ignition energy input
- Spread speeds between 1500 m/s and 3400 m/s.
- Detonation pressures between 15 and 20 bar
- Detonation propagation occurs in the form of a spatial wave structure, depending on the concentration, temperature and pressure in the mixture.

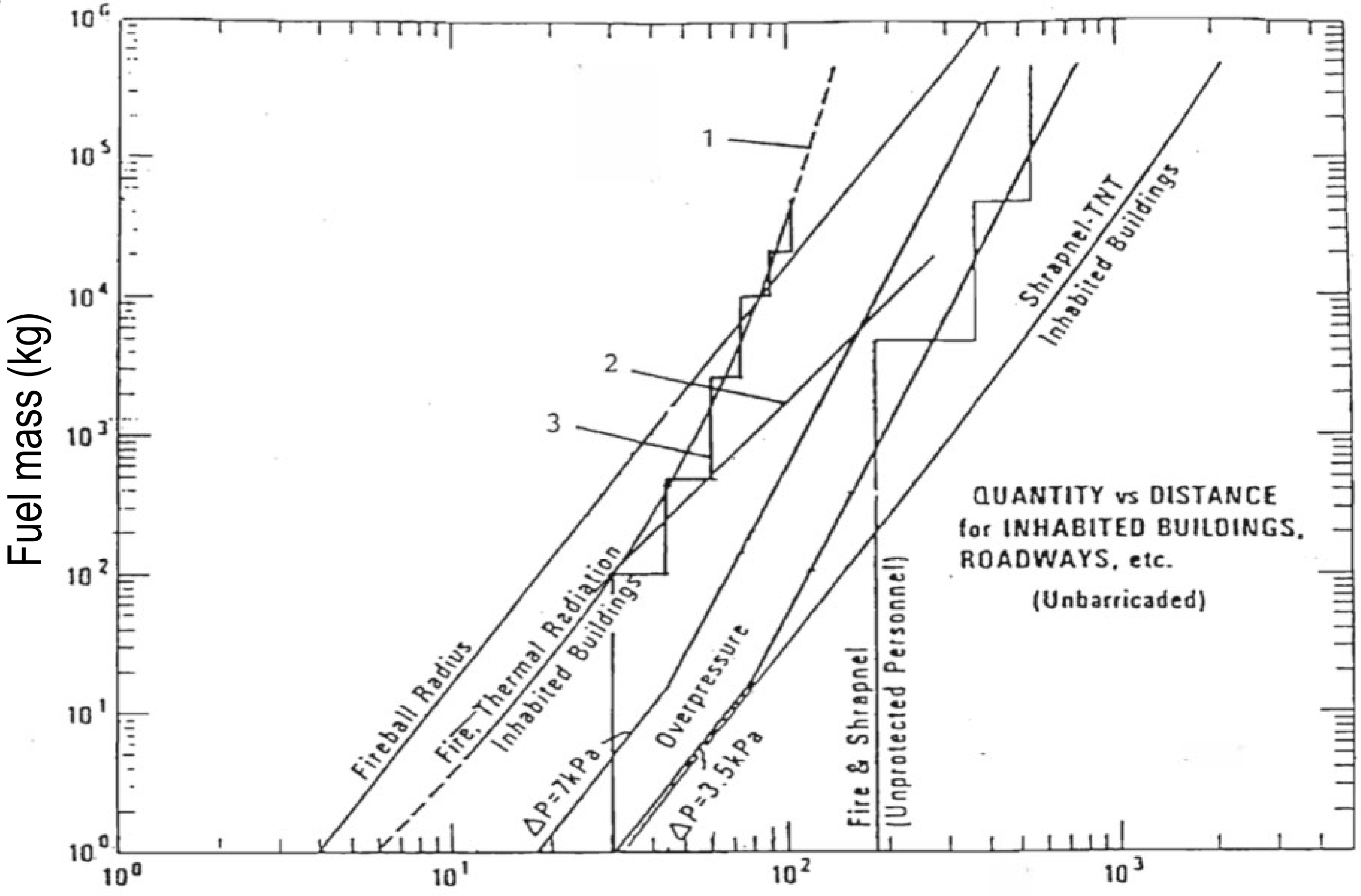



Geraint Thomas: Some observations on the initiation and onset of detonations; The Royal Society publication 2012

# CONSEQUENCE: SAFETY DISTANCES TO H2 SYSTEMS

Safety distances for specified environments are defined depending on the amount of fuel and tolerable values for overpressure or thermal load.

They are different for inhabited buildings, public roads, industrial plants and laboratories




National research Council Canada; „Safety guide for hydrogen“; NRC ; Ottawa, Ontario; 1987

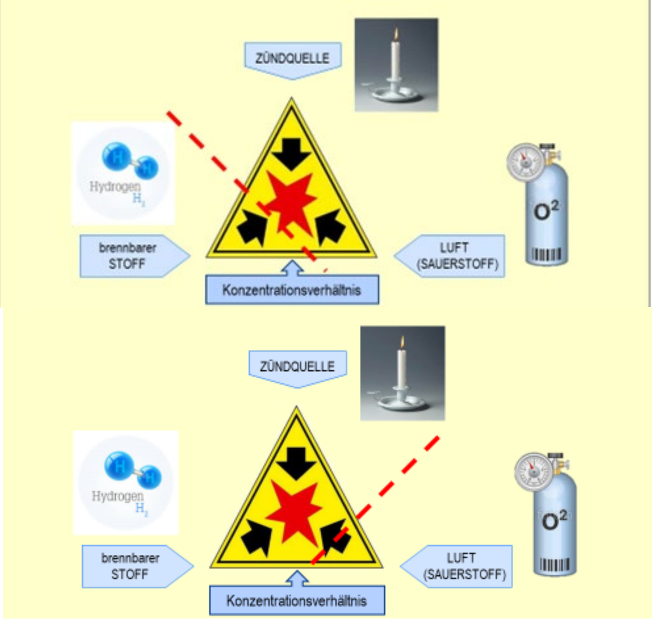
# BASIC ELEMENTS OF SAFETY CONCEPTS FOR HYDROGEN

# RISK ANALYSIS AS THE STARTING POINT AND THE BASEMENT

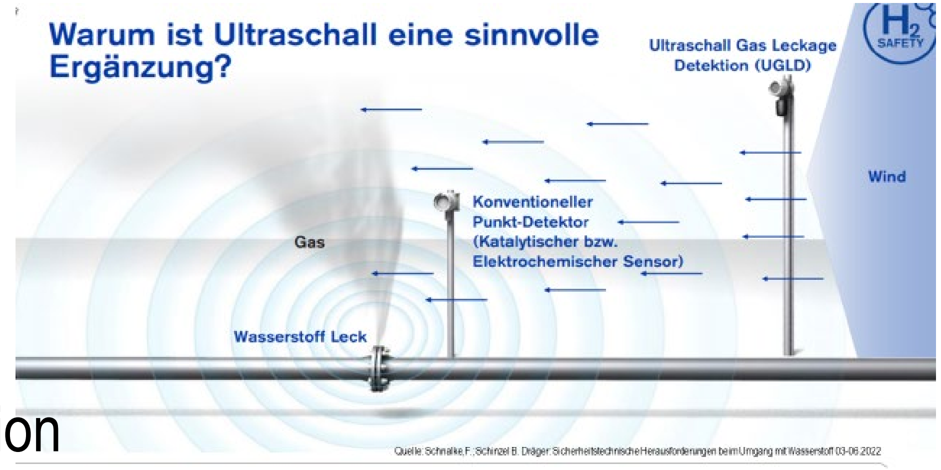
- The manufacturer must perform a risk analysis using one or more methods according to IEC 31010, Annex B, i.e.
  - HAZOP, fault tree analysis (FTA), FMEA, Markov analysis
- and/or ISO 12100 "Safety of machines".
- Normal operation and relevant error conditions must be observed during this process
- When planning the system, the requirements of ISO 12100 must be followed.


Source: Sunfire

# 1. PRIMARY SAFETY MEASURES: AVOIDANCE OF THE ESTABLISHMENT OF EXPLOSIVE MIXTURES



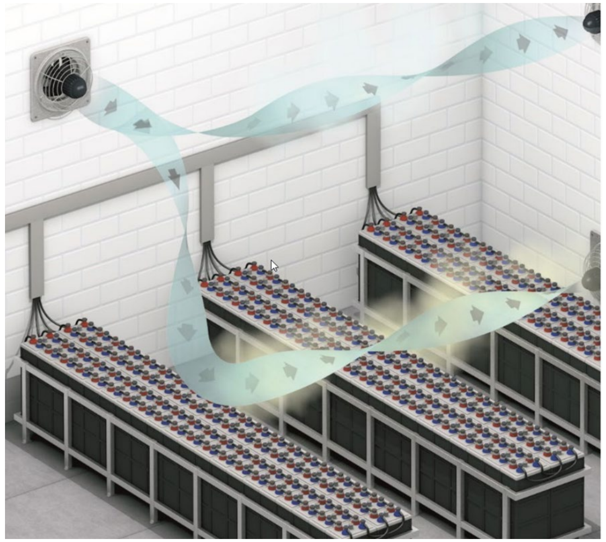

1. Tightness of equippment
2. sufficient natural ventilation




3. Surveillance of gas concentration
4. At > 25% LEL switch on of technical ventilation

**Reliability of all safety functions is of highest importance! (SIL)**

5. Surveillance of gas concentration at > 25 % LEL switch of the complete facility



Maica/ Dräger

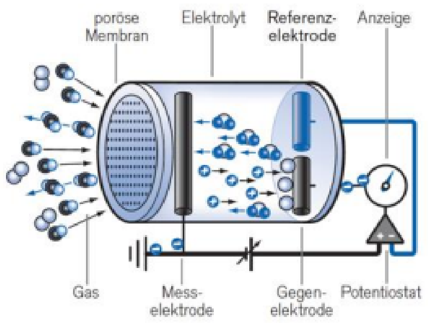
# LEAK TIGHTNESS OF THE SYSTEM PARTS: EN 1127-1:2019: ANNEX B

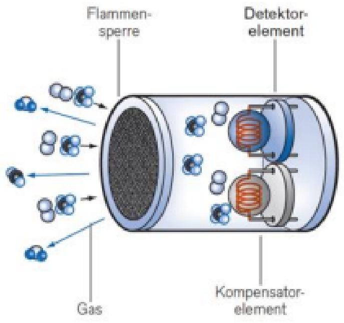
- **Normal leak tightness**: No release is expected during normal operation; if this does occur, it is rare and for a short time.
- **Increased leak tightness**: No release at all is expected, and no explosive atmosphere can form in the surrounding environment
- One potential way to achieve increased leak tightness is the use of continuous gas monitoring with an appropriate degree of functional safety
- **ISO 26142**: Stationary gas warning equipment for H2

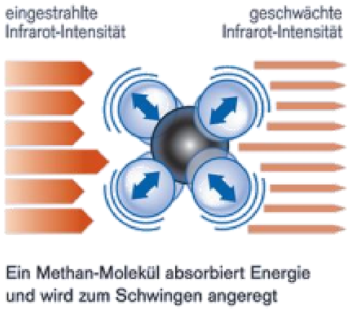


VDI, Trotec

# BASIC TECHNOLOGIES FOR GAS-DETECTION




**Electrochemical Sensor**
work similar to batteries and fuel cells.

- Target substance reacts **chemically** and creates an electrical charge between two electrodes.
- The **signal strength** is proportional to the gas concentration

**Catalytic bead sensor (CatEx)**
**oxidize** combustible gases releasing heat.

- A suitable temperature-controlled catalyst material is used, which is also **heated up** measurably by the heat of reaction.
- This **slight increase** in temperature is a **measure** of the gas concentration.

**Infrared sensor (IR)**
measure the change in **intensity** of **infrared radiation** absorbed by target substances.

- Infrared is weakened by C-H but not by H-H bonds.
- - Methane can be measured with an IR sensor, but **not hydrogen**

Informationen und Bilder aus DrägerSensor® & Gasmessgeräte-Handbuch, 4. Ausgabe, 2018 Dräger Safety AG & Co. KGaA

# SECONDARY SAFETY MEASURES: EXPLOSION PROTECTION BY AVOIDING IGNITION SOURCES

- When it comes to Ex protection, zone classification as per IEC 60079-10-1 must be performed and, if necessary, ignition protection methods as per IEC 60079-0 ff. must be implemented.

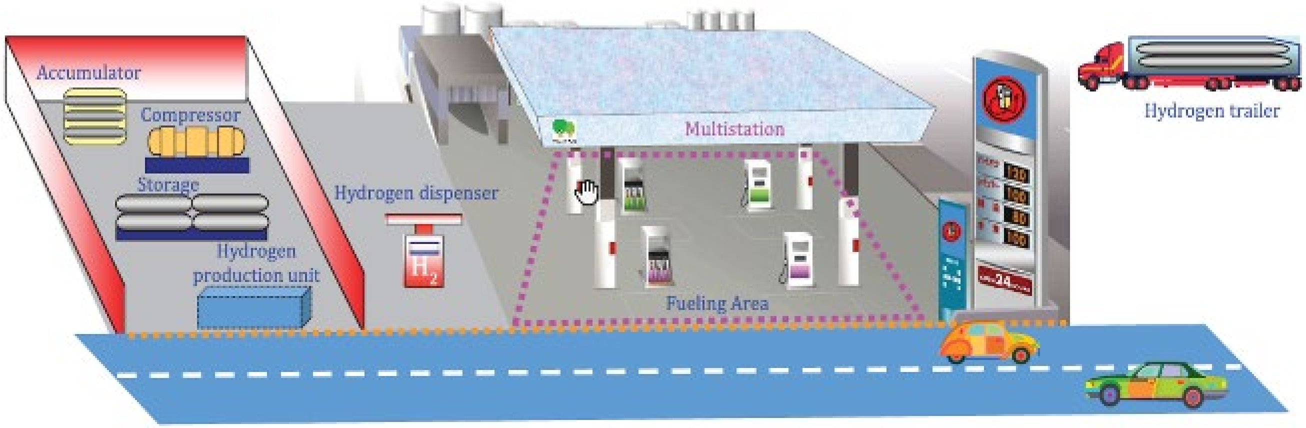
- Certified equipment with IIC or IIB+$H_2$ rating must be installed

- The specific Ex conditions in oxygen-rich atmospheres must be observed.

NEL

# COMPETENCE FOR CORRECT PLANNING, INSTALLATION, OPERATION, INSPECTION AND MAINTENANCE IS REQUIRED!

- Zone classification as per IEC 60079-10-1
- Installation as per IEC 60079-14
- Types of protection with reference to IEC 60079 ff. and IEC 80079-36/37
- Inspection and maintenance as per IEC 60079-17

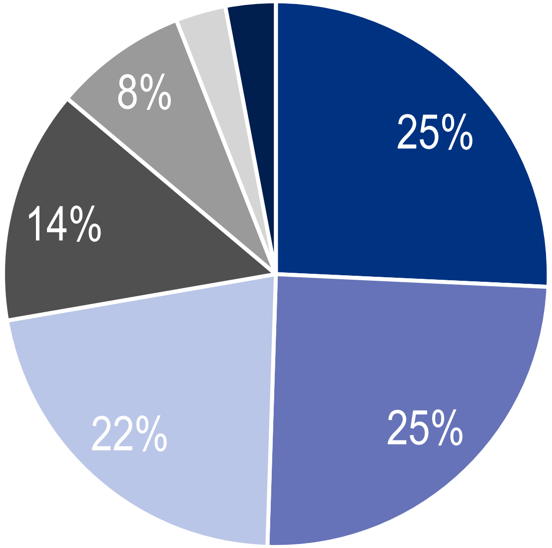




ISO 19880-1

# ANALYSIS OF ACCIDENTS IN HYDROGEN APPLICATIONS

Ordin, P.M.: Review of Hydrogen Accidents and Incidents in NASA Operations 1974

- Operational and work area deficiencies
- Procedural deficiencies
- Design deficiencies
- Planning deficiencies
- Malfunctions
- Material failures
- Material incompatibilities




**Two main goals**

- Minimize potential human error
  => **Training**
- Develop systems that remain robust in the event of human error

NASA, Der Spiegel;

# WHAT DOES IECEX DO TO ESTABLISH A SUFFICIENT LEVEL OF SAFETY FOR HYDROGEN APPLICATIONS?

## Goal 1: Minimize potential human error:

- IECEx added Hydrogen specific competence elements to the Recognized Training Provider (RTP) Program and
- Established Unit 11: Basic knowledge of the safety of hydrogen systems
- Unit 11 works in conjunction with two or more standard Units of OD 504
- Unit 11 refers directly to ISO/TR 15916

IECEx OD 504

Edition 5.0 2022-10

IECEx
OPERATIONAL DOCUMENT

ards Relating to Equipment for Use in
m)

sonnel competence for explosive

assessment outcomes

AGU

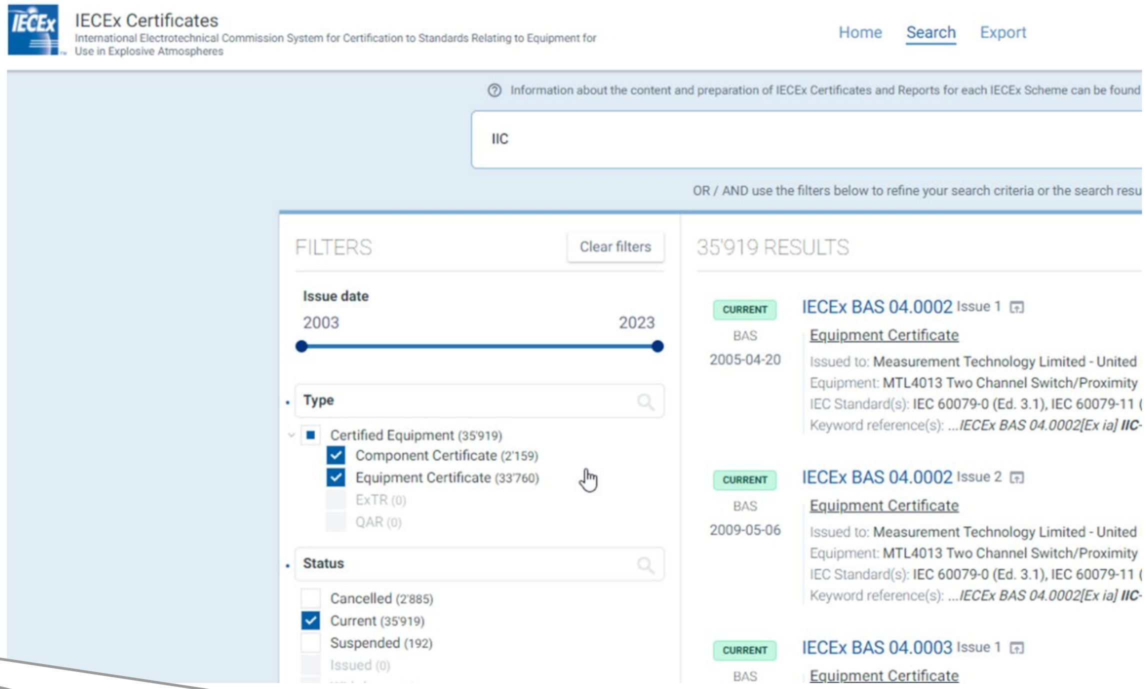
# CANADIAN HYDROGEN INSTALLATION CODE – 4.2 INSTALLER QUALIFICATIONS, AND OPERATOR TRAINING

- Only qualified personnel shall be responsible for the installation of hydrogen equipment covered by this code.
- Upon completion of an installation , the installer shall train the system operator on the proper and safe use of all hydrogen equipment covered by this code.
- At a minimum, system operator training shall cover basic hydrogen properties; safety aspects, including the safe handling and operation of hydrogen systems…

# WHAT DOES IECEX DO TO ESTABLISH A SUFFICIENT LEVEL OF SAFETY FOR HYDROGEN APPLICATIONS?

**Goal 2: Develop systems that remain robust in the event of human error:**

- IECEx keeps **35,919 current IIC** – Product certificates in the online database
- OD 290 is the basis for harmonized procedures for IECEx certification of equipment, components and systems **associated with the production, dispensing and use of gaseous hydrogen**




OD 290 refers closely to the relevant Hydrogen standards like ISO 19880-X and to IEC 60079-46: Equipment assemblies

# CERTIFICATION REQUIREMENTS

**5 HYDROGEN EQUIPMENT**

**5.1 HYDROGEN EQUIPMENT TO BE INSTALLED**

Hydrogen-generating equipment for non-process end use, hydrogen utilization equipment, hydrogen-dispensing equipment, hydrogen storage containers, hydrogen piping systems and their accessories shall be certified or approved prior to installation.

shall be certified

**7.7 COMPRESSORS AND COMPRESSOR PACKAGES**

**7.7.1 General**

Only compressors that are designed for hydrogen systems shall be used.

Compressors that are an integral part of certified or approved hydrogen-generating equipment need not comply with the provisions of Clause 7.7.

**7.8.1.3** Subject to the approval of the AHJ, stationary containers for compressed gaseous hydrogen storage originally intended for transportation and onboard use shall be certified to one of the following documents:

a) CSA B51, Part 2;

b) ISO 11119;

c) ISO 19881;

Dispensers shall comply with the requirements of the document CSA/ANSI HGV 4.1. Dispenser validation testing for light-duty vehicles shall be performed in accordance with the document CSA/ANSI HGV 4.3.

NOTE — The document CSA HGV 4.9 focuses on hydrogen key fuelling station components and protocols by setting requirements and referencing appropriate standards, e.g., documents SAE J2601 for hydrogen fuelling protocol, SAE J2799 for communication with a hydrogen-fuelled vehicle, CSA/ANSI HGV 4.1 for hydrogen dispensers and CSA/ANSI HGV 4.3 for hydrogen dispenser validation testing.

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