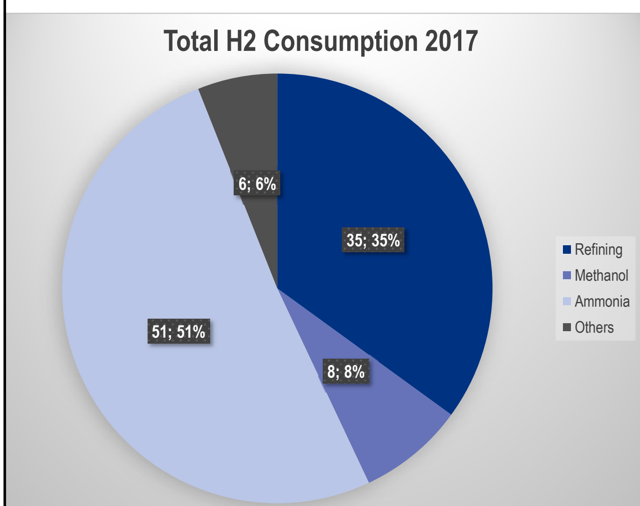
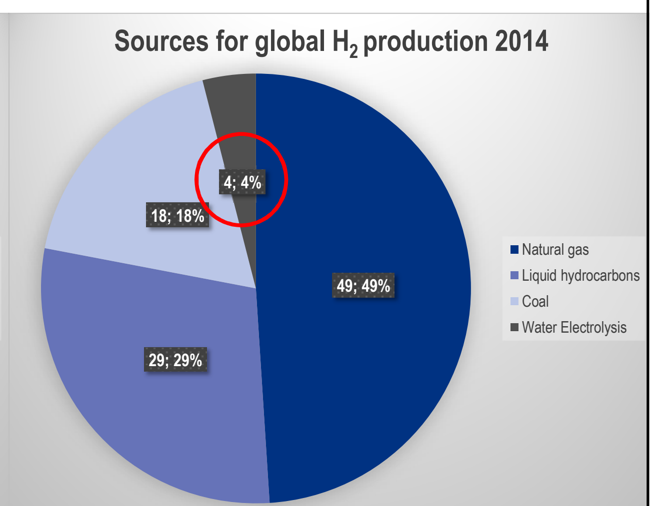
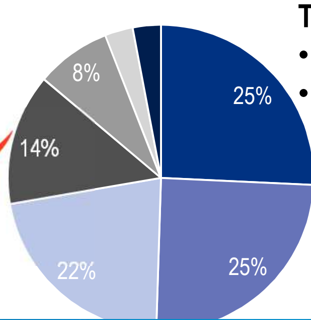
GLOBAL HYDROGEN PRODUCTION IN 2019 > 70 MILLION TONS





ANALYSIS OF ACCIDENTS IN HYDROGEN APPLICATIONS

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



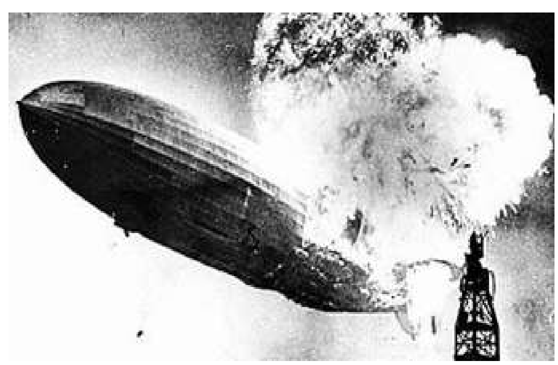
Two main goals

- Minimise potential human error
- Develop systems that remain robust in the event of human error

NASA, Der Spiegel;

LZ129 HINDENBURG AIRSHIP, 6TH MAY 1937, LAKEHURST (NJ, USA)

- Clear to see: No pressure wave => no explosion!
- Shortly before the ignition, there was a severe storm. There were still significant differences in potential between the atmospheric layers and the ground
- The airship gained the potential of the surrounding air
- Wet anchoring ropes caused potential equalisation with the ground, during which sparks were generated.
- This caused the metallised paint (composition similar to present-day rocket fuel) on the airship hull to ignite, which led to combustion of the hydrogen.



fr.de

HERAEUS, HANAU, 5TH OCTOBER 1991

- Rupture of a 100 m^3 hydrogen tank and maximum operating pressure of 45 bar
- Since the accident occurred on a Saturday morning, only 23 people suffered minor injuries, but the material damage amounted to over €100 million
- Caused by voltage cracks in a weld seam in the 22 mm-thick tank wall
- The inspection and production processes for tanks of this type were subsequently changed

Hanauer Anzeiger

HYDROGEN BALLOON CRASH, 1997, KIENBERG (HAVELLAND)

- Balloon trip from Bitterfeld
- A balloon came within 60 m of the transmission masts of the strong KW transmitter in Nauen
- This induced a strong current in the ring-shaped nylon rope on the top of the balloon, which was made conductive by its metal fibres.
- This led to heating due to the high frequency, the basket plummeted to the ground and the balloon was destroyed (combustion and deflagration).
- Four fatalities

ARD

OSLO HYDROGEN FILLING STATION, 12TH JUNE 2019

- Two people suffered minor injuries near the filling station.
- Week-long interruption to water supply in Norway.
- Caused by an assembly error on a high-pressure hydrogen tank.
- As a result, stricter safety precautions were introduced during assembly.

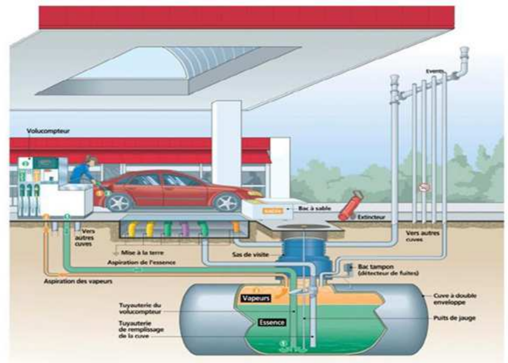
Watson.ch

FUKUSHIMA NUCLEAR POWER STATION, 2011

- As the result of a tsunami caused by a natural disaster of "biblical proportions", all 4 emergency cooling systems failed because they were flooded
- Heat build-up in the reactor cores caused the zirconium shells around the fuel rods to break down
- This meant that hydrogen gas mixed with air and collected in the buildings
- In the end, this led to ignition and explosions

HOW TO ADDRESS HAZARDS OF HYDROGEN?

V.S.



www.gefahrengut-online.de; Fdms-dsp.fr

Closed industrial facilities; operated by competent operators

Public locations; usual crowded; operated by non – experts/lays

SAG
Progress in Aluminium

Home Products Development Career Company

10 important questions about hydrogen

01 | What is hydrogen? +

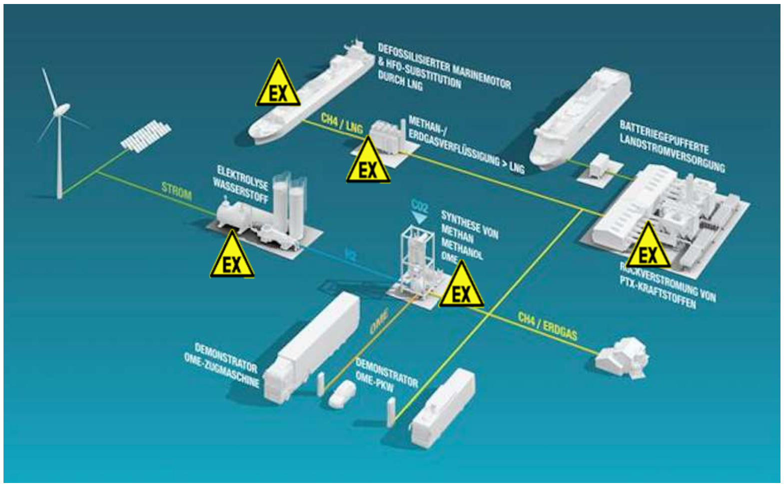
02 | How does the energy density of hydrogen compare to conventional fuels? +

03 | How dangerous is the use of hydrogen? +

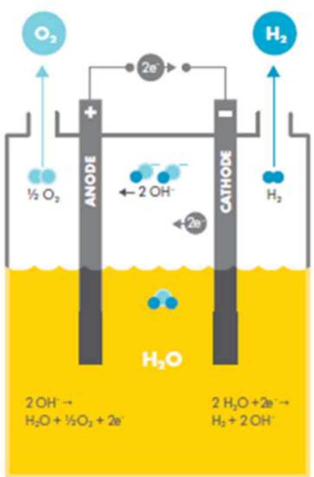
04 | Is hydrogen explosive? –

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

POWER-TO-X TECHNOLOGY



ELECTROLYSIS



	Temperature °C	Electrolyte	Plant size		Efficiency	Purity H_2	System costs	Lifespan	Maturity level
Alkaline Electrolysis (AE)	60 - 80	Potassium-hydroxid	0.25 - 760 Nm³ H_2/h	1.8 - 5,300 kW	65 - 82%	99.5% - 99.9998%	1,000 - 1,200 €/kW	60,000 - 90,000 h	Commercially used in industry for the last 100 years
Proton Exchange Membrane Electrolysis (PEM)	60 - 80	Solid state membrane	0.01 - 240 Nm³ H_2/h	0.2 - 1,150 kW	65 - 78%	99.9% - 99.9999%	1,900 - 2,300 €/kW	20,000 - 60,000 h	Commercially used for medium and small applications (<300 kW)
Anion Exchange Membrane Electrolysis (AEM)	60 - 80	Polymer membrane	0.1 - 1 Nm³ H_2/h	0.7 - 4.5 kW	N/A	99.4%	N/A	N/A	Commercially available for limited applications
Solid Oxide Electrolysis (SOE)	700 - 900	Oxide ceramic	Until now at experimental stage in laboratories		85% (lab)	N/A	N/A	approx 1,000 h	Experimental stage

E4tech 2014; IEA 2015b; own diagram

ISO 22734: HYDROGEN GENERATORS USING WATER ELECTROLYSIS – INDUSTRIAL, COMMERCIAL AND RESIDENTIAL APPLICATIONS (2019)

- 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 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
- The specific Ex conditions in oxygen-rich atmospheres must be observed
- Maximum concentration of released hydrogen is 1%, with the use of gas detectors
- Emergency stop and shut down measures

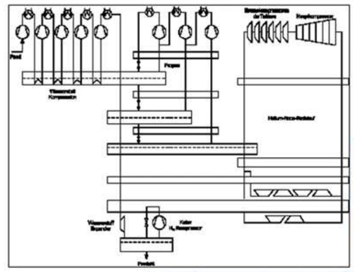
ISO 22734: HYDROGEN GENERATORS USING WATER ELECTROLYSIS – INDUSTRIAL, COMMERCIAL AND RESIDENTIAL APPLICATIONS (2019)

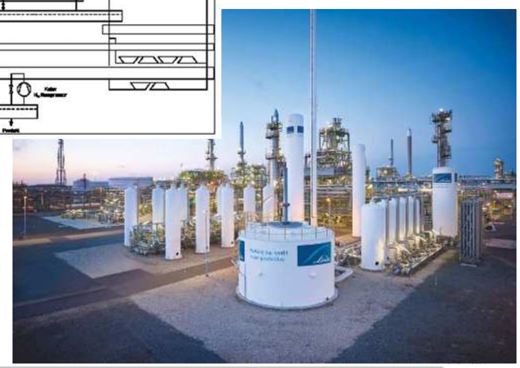
When it comes to electrolysers, there are also requirements regarding the **compression of the generated hydrogen**. Among other requirements, it stipulates that:

- They must be generally suitable for compression of gaseous hydrogen under the specified pressure and temperature conditions
- They must be equipped with suitable pressure relief systems
- An automatic emergency shut-off in the event of impermissible high pressures or temperatures, or insufficient suction pressures must be present
- Information for the use of compressors for use in hydrogen filling stations can be found in ISO 19880-3: Gaseous hydrogen-fuelling stations – Part 3: Valves

HYDROGEN LIQUEFACTION

- Liquefaction at -253 °C
- In liquid state, H_2 has a significantly higher energy content per unit of mass (gravimetric energy density)
- Similar process and similar conditions to liquid natural gas (LNG)
- Compression of H_2 to between 60 and 80 bar with subsequent multi-stage process until liquefaction (Joule Thomson effect)
- 30% of the stored energy is required for liquefaction!





EXTRACTION FITTINGS

- Zone 1 at close range
- Zone 2 at greater distances

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

HYDROGEN CYCLE

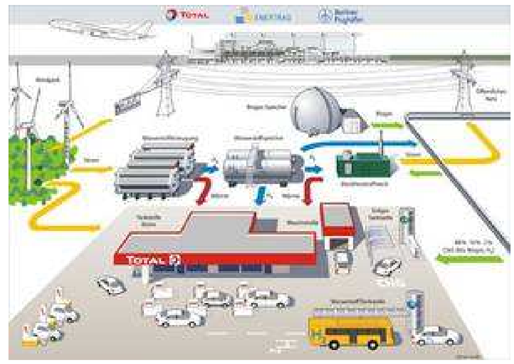
TOTAL H2 MOBILITY CEP DAIMLER Linde sunfire

fahrspaß24

golem.de

HYDROGEN FUELLING STATIONS ISO 19880-1:2020

- The following should be considered potential sources of hazards:
- Local H_2 production units
- The entire H_2 supply system (from an external perspective)
- Compressors
- Tanks
- Non-welded pipeline connections
- Hydrogen distribution up to the vehicles



Leuna - echo

All areas must be subjected to a systematic risk assessment

HYDROGEN FUELLING STATIONS ISO 19880-1:2020

- Must be designed and operated so that the formation of explosive atmospheres is
  - prevented
  - minimized
  - detected
  - controlled

Primary explosion protection (prevented, minimized, detected)

Secondary and tertiary *explosion protection* (controlled)

- 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

HYDROGEN FUELLING STATIONS ISO 19880-1:2020 COMPRESSORS:

- Risk assessment and development of suitable countermeasures
- No sources of ignition may be present
- Vibration and displacement of compressors must be compensated for
- Temperature and pressure levels, as well as additional parameters that must be observed during liquefaction of hydrogen, must be suitably monitored

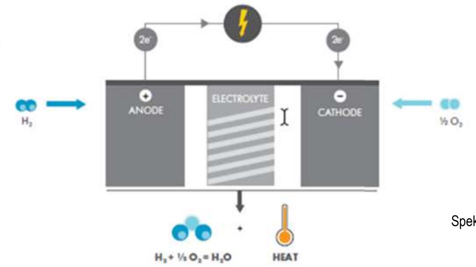
Mehrer.de

TRBS 751 FILLING STATION GAS DISPENSING POINTS

- Mandatory risk assessment according to TRBS 1111 and TRGS 400
- The aim is to protect employees and other people from particular hazards posed by pressure, fires or explosions
- Observation of normal operation and malfunctions
- Typical hazards include failure of the vacuum insulation on storage containers and boil-off effects

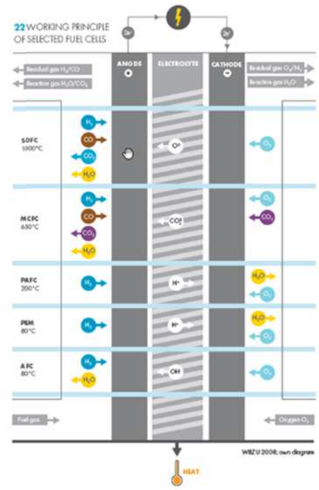
Concertare.de

FUEL CELLS



Spektrum der Wissenschaft

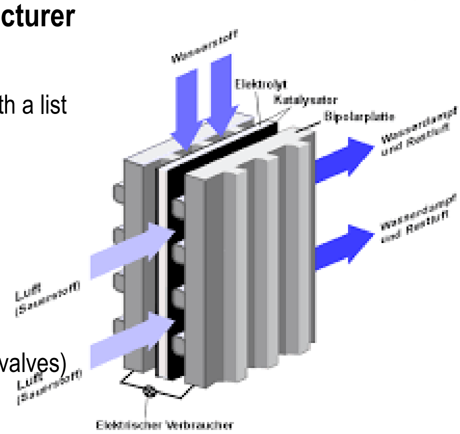
Source: Shell Hydrogen Study 2017



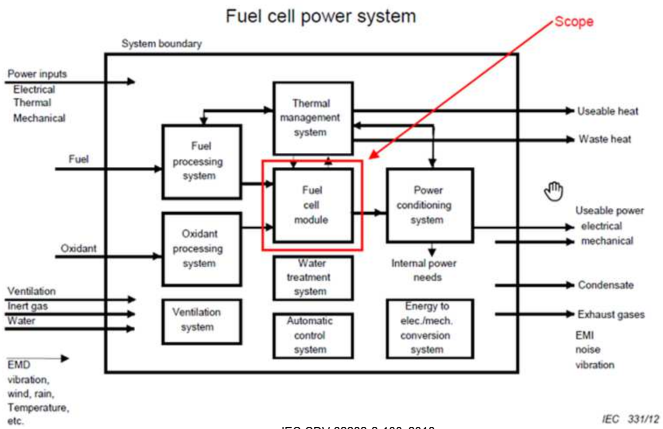
Fuel cell type	Temperature range °C	Electrolyte	Electrical performance	Fuel	Oxidant	Efficiency η_{el} (H_2)	Investment costs USD/kW$_{el}$	Life expectancy (h)	Market development	Application
AFC	60 - 90	Potassium hydroxide	Up to 250 kW	H_2	O_2 (pure)	50 - 60%	200 to 700	5,000 to 8,000	Established for decades, but limited to specialised applications	Space travel, submarines
PEMFC	50 - 90 (LT) up to 180 (HT)	Polymer membrane	From 500 W to 400 kW	H_2, gas, syngas, biogas, methanol (external reforming)	O_2	30 - 60% (depending on size and application)	3,000 to 4,000 (stationary) ~500 (mobile)	60,000 (stationary) 5,000 (mobile)	Early market/ mature leading fuel cell type	Vehicle drivetrains, space travel, micro + block-type CHP, backup power
PAFC	160 - 220	Phosphoric acid	Up to several 10 MW	H_2, gas, syngas, biogas, methanol (external reforming)	O_2	30 - 40%	4,000 to 5,000	30,000 to 60,000	Mature (low volume)	Decentralised power generation, block-type CHP
MCFC	600 - 700	Carbonate melt	From a couple of 100 kW to several MW	H_2, gas, syngas, biogas, methanol (internal reforming)	O_2	55 - 60%	4,000 to 6,000	20,000 to 40,000	Early market/market introduction (especially for bigger plants)	Power plants (base load), CHP (process heat/steam)
SOFC	700 - 1,000	Solid ceramic oxide	From a couple of kW to several MW	H_2, gas, syngas, biogas, methanol (internal reforming)	O_2	50 - 70%	3,000 to 4,000	up to 90,000	Mature (volumes rising)	Power plants, CHP (process heat/ steam), micro + block-type CHP

IEC NORMEN (TC 105): IEC 62282-2-100 (CDV) FUELL CELL TECHOLOGIES – PART 2 -100: FUEL CELL MODULES

- **A comprehensive risk analysis shall be done by the manufacturer including a written documentation of this:**
  - Identification of all reasonably foreseeable hazards (see Appendix A with a list of typical hazards)
  - Evaluation of the probability of occurrence and ist foreseeable severity
  - Elimination of all riscs or reduction to an acceptable level.
- Alternatives for risk reducing measures:
  - Inherent safe constructions and/or
  - passive control of energy release in safe areas (busting discs, release valves) and/or
  - safety related control functions Handle residual risks by means of organizational methods (operations instructions, warning labels etc.)



FUEL CELL SYSTEM



IEC CDV 62282-2-100: 2018

Fuel cell modules as components of fuel cell systems must be assessed in terms of their overall safety when interacting with all system components! For example, the specification of leak rates under operating conditions is important to determine ventilation for the entire system.
Comprehensive user information is therefore required!

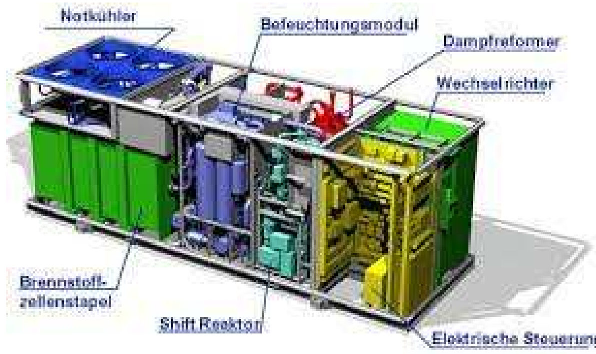
IEC 62282-3-100: 2020 & 62282-5-100:2020 SAFETY OF STATIONARY/PORTABLE FUEL CELL ENERGY SYSTEMS

- Risk analyses such as for fuel cell modules
- Same requirements for material properties and process stability as required for modules
- Hazards due to the accumulation of flammable atmos-pheres must be eliminated!
- Areas containing sources of combustible gases or vapors must be identified and classified
- In these areas, dilution to a maximum fuel concentration 25% of the OEL is ensured and monitored to the greates possible extent
- This is not possible in spaces classified as **hazardous areas**.

Fuel Cell Works.com

IEC 62282-3-100: 2020 & 62282-5-100:2020 SAFETY OF STATIONARY/PORTABLE FUEL CELL ENERGY SYSTEMS

- Classification using computer-aided fluid-dynamic investigations, indicator gas and other methods specified in IEC 60079-10-1.
- All devices that are used inside the hazardous areas must be eliminated as potential sources of ignition by:
  - Ensuring that the equipment used corresponds to the zone
  - Ensuring that the surface temperature of any equipment is no more than 80% of the ignition temperatures of the fuels
  - Providing protection against electrostatic charge
  - Limiting catalytic material reactions



Chemgapedia.de

IEC 62282-3-100: 2020 & 62282-5-100:2020 SAFETY OF STATIONARY/PORTABLE FUEL CELL ENERGY SYSTEMS

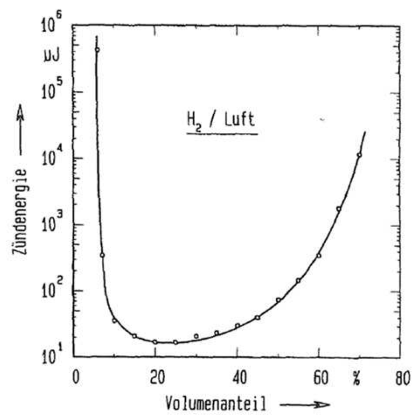
- Alternative: Protection using pressurized enclosure in accordance with IEC 60079-2
- Trace heating as per IEC 60079-30-1
- To limit the anomalous release of fuel over 25% of the OEL, passive, active or combined measures must be implemented:
  - Passive: Including mechanical measures
  - Active: Flow measurements, gas measurements with system shutdown if the limit value is exceeded

Source: BMW

DIN EN IEC 60079-10-1: HAZARDOUS AREAS CLASSIFICATION OF GAS HAZARDOUS AREAS

Annex H (informative) hydrogen

- Explosion range: (4 ... 77) Vol%
- If H2 is mixed in with other gas mixtures, the explosion group IIC or IIB + H2 should be assumed from 30 vol%.
- Low density of H2 => strong buoyancy, but with increasing dilution of the hydrogen content in air the buoyancy decreases!
- Hydrogen is therefore likely to collect in rooms above.



DIN EN IEC 60079-10-1: HAZARDOUS AREAS CLASSIFICATION OF GAS HAZARDOUS AREAS

Annex H (informative) hydrogen

- Description of the evaporation of released liquid H2 (see above)
- Fire and ignition behaviour of H2 gas clouds
- Combustion characteristics of H2:
- Flames are difficult to notice: colourless, little UV radiation
- A localized hydrogen fire is preferable to the formation of a growing hydrogen plume!
- Particular danger if high pressure is released!

Wissenschaft.de

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