EN – 610: HYDROGEN ENERGY

Instructor

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Course Evaluation

SLOT 6: Wed and Fri: 11-05 AM to 12-30 PM

01 Quizzes: 2+2 (5 points each – Total 20)

02 Mid-semester Exam (20 Points)

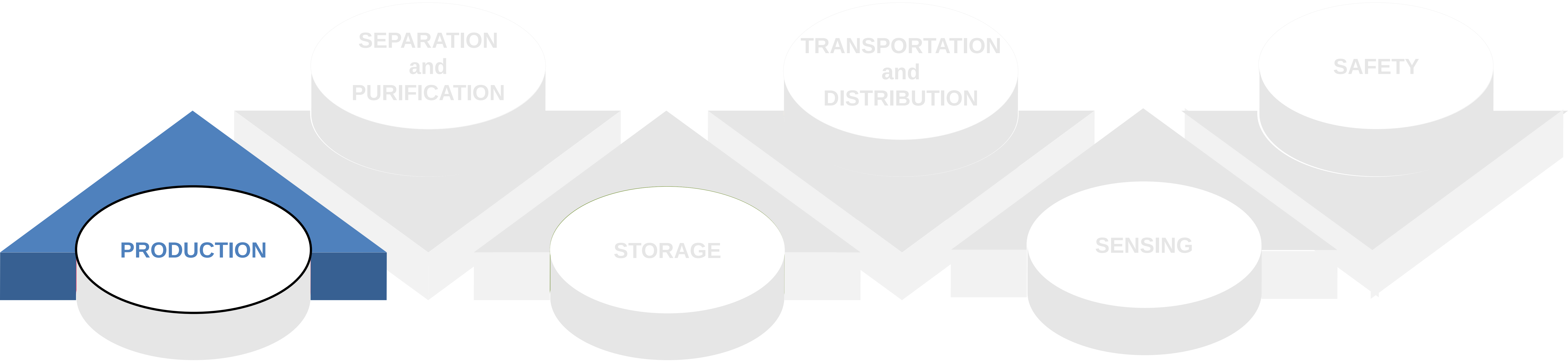
03 End-semester Exam (30 points)

04 Projects - Groups of 4, each (30 points)

80% Attendence is Compulsory

Course Contents

HYDROGEN TECHNOLOGIES



- **Production from Hydrocarbons**
- **Oxidative/Non-oxidative Processes**
- **Gasification**
- **Nuclear Energy**
- **Renewables: Solar, Wind, *etc***

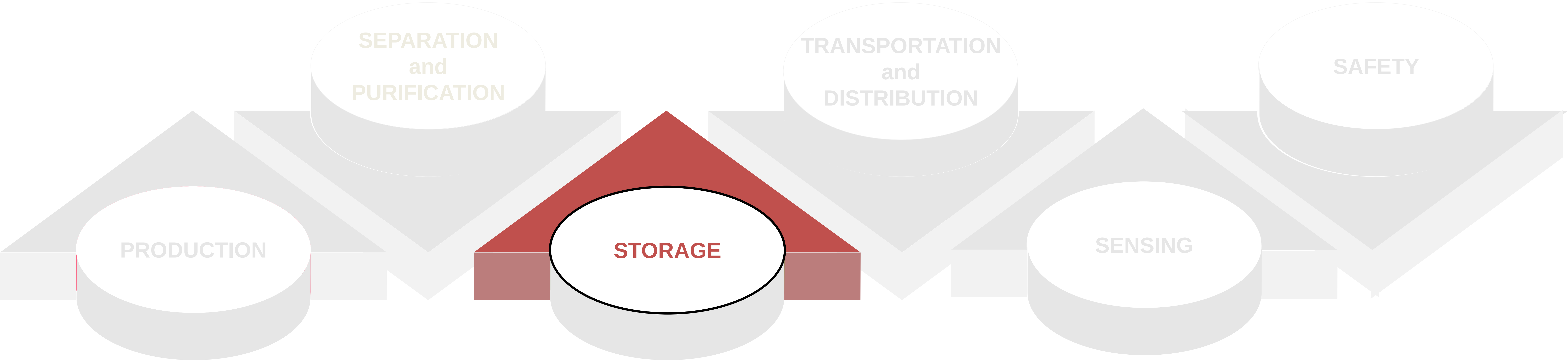
Course Contents

HYDROGEN TECHNOLOGIES

- **Pressure Swing Adsorption**
- **Solvent Based Adsorption**
- **Membrane Separation**
- **Cryogenic Separation, *etc***

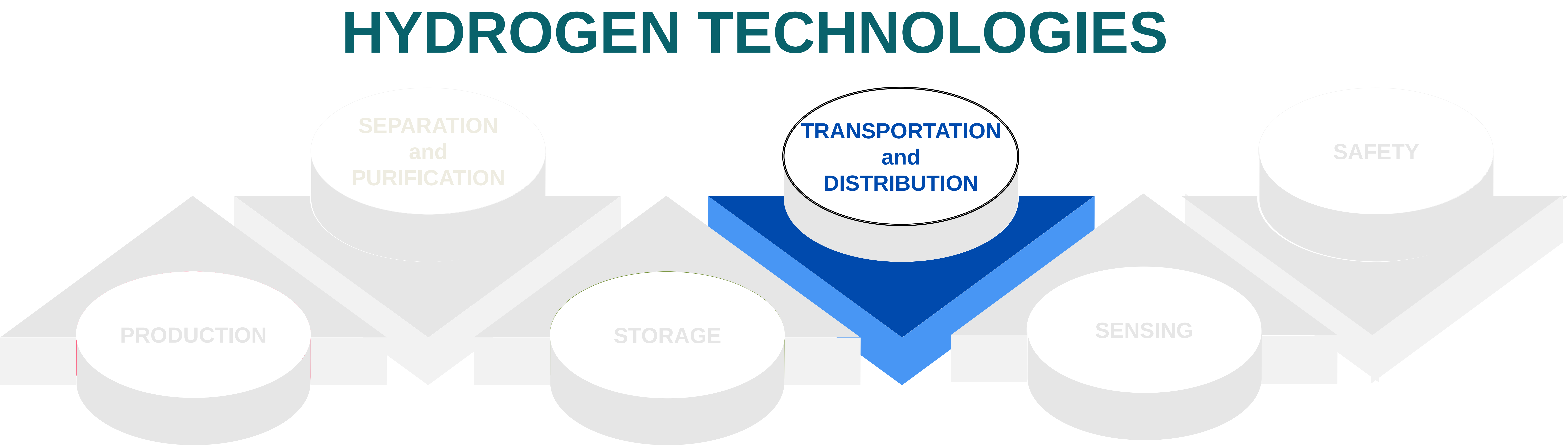
Course Contents

HYDROGEN TECHNOLOGIES



- **Compressed Storage**
- **Liquid-state Storage**
- **Solid-state Storage**
- **Materials for storage - Metal, Complex, Chemical Hydrides, High-surface Area Materials, *etc***
- **Design Aspects**

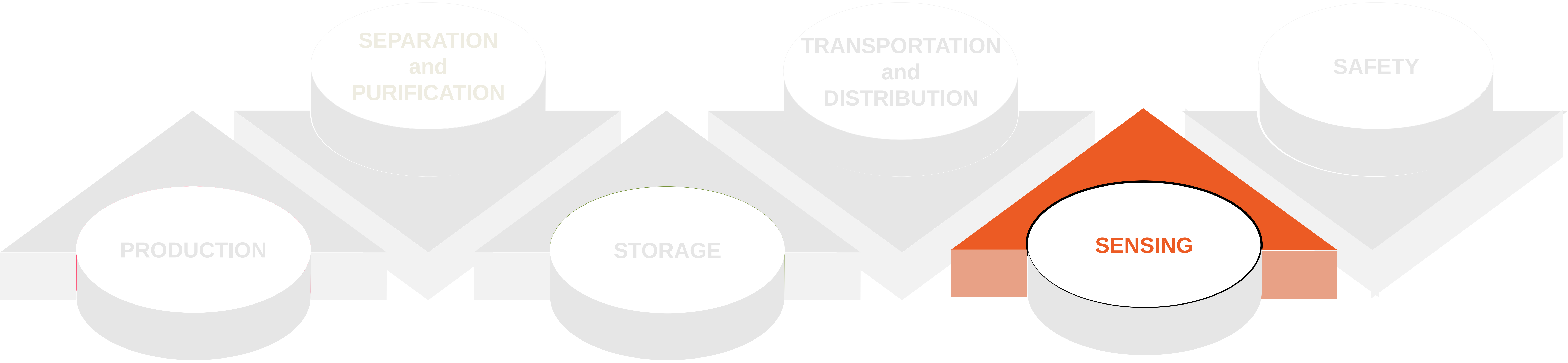
Course Contents



- Distance and Demand Based Transportation Choices
- Pipe-based versus Tank-based transportation
- LOHCs
- Other aspects

Course Contents

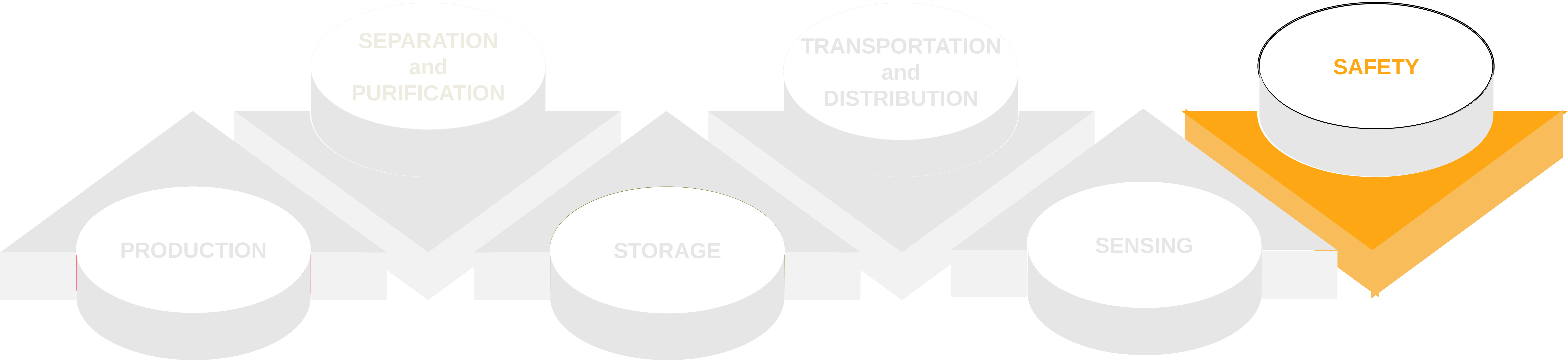
HYDROGEN TECHNOLOGIES



- **Methods using Thermal-conductivity**
- **GS;MS-based Measurements; Laser-based Gas Analysis**
- **Solid-state Sensors: Applications and Industrial Scalability**

Course Contents

HYDROGEN TECHNOLOGIES



- History of Accidents
- Physical and Chemical Hazards
- Properties of Hydrogen leading to Hazards
- Hazard Spotting, Evaluation and Safety Guidelines; Hazard Prevention Measures
- Safety Codes and Standards

Study Material

01 Review Papers (will be announced in the class, timely)

02 Hydrogen fuel: Production, transport and storage by Ram B. Gupta, CRC Press, 2009 edition

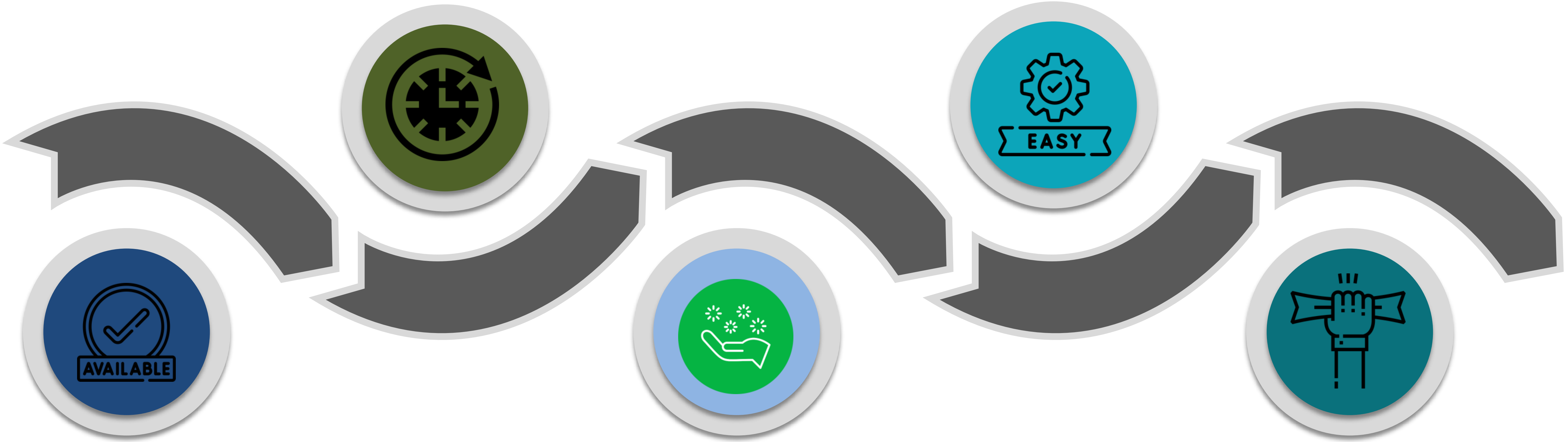
03 IEA Reports

04 Lecture Notes: To be taken during the lectures

Requirements from a Fuel

INEXHAUSTIBLE

CONVENIENT



EASILY AVAILABLE

CLEAN

AWAY FROM FOREIGN CONTROL

Why Hydrogen?

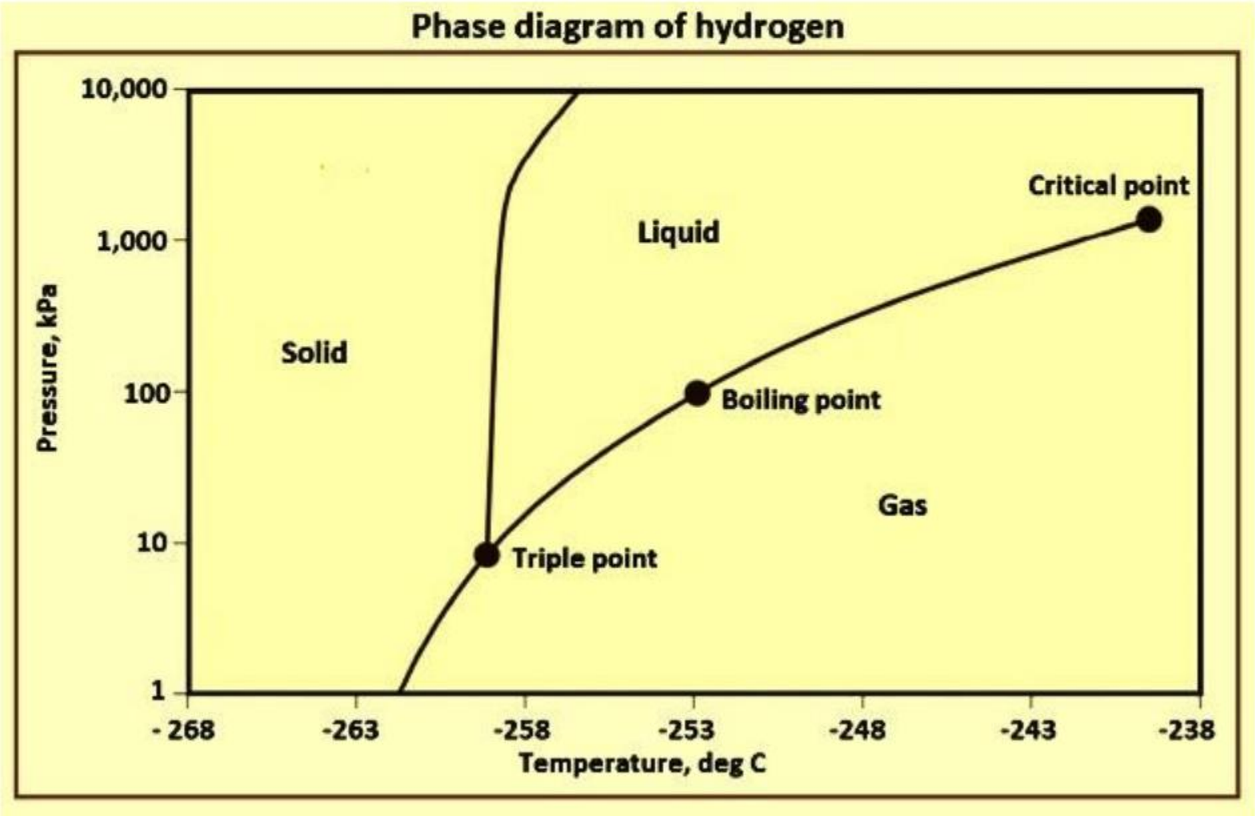
- Most Abundant in the Universe
- Richest in Energy Density: 140 MJ/kg
- Produces Water as By-product
- Reduced Dependency on Fossil Fuel
- Promotion of Domestic, Sustainable and Diverse Sources
- Reduced GHG Emissions
- More Efficient Power Generation
- Promotion of Hydrogen Technologies such as Fuel Cells
- Viable with existing Conventional Technologies
- Widely Used in Chemical Industries and Refinaries
- Easily integrated with Renewbles
- Multiple Feedstocks; Matured Production Technologies

Properties of H_2

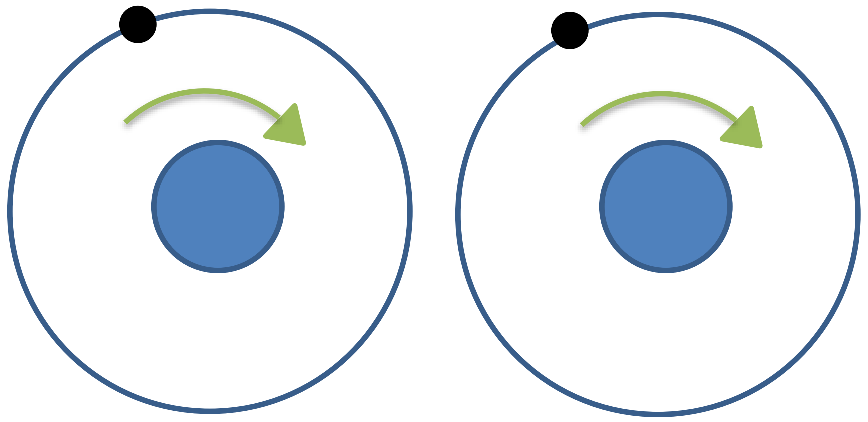
- Lightest element with 1 proton and 1 electron
- 14x lighter than air
- Diffuses faster than any other gas in air (diffusion coefficient: 0.61 cm^2/s)
- High Buoyancy: Rises Faster than any other gases
- Major Constituent of Water and Organic Compounds
- Isotopes: Deuterium/Tritium - Trace in nature but can be prepared by nuclear reactions
- Pronounced Solubility in Metals

- Colourless, odourless, tasteless
- Density of Hydrogen: 0.084 kg / m^3 - NTP
- Condenses to Liquid at -253^{o}C and Solid at -259^{o}C
- Ionization Potential of -13.54 eV
- Low solubility in solvents

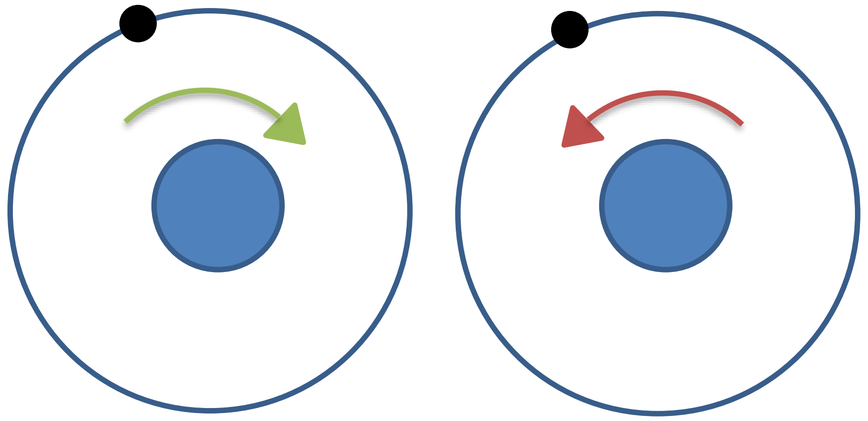
Properties of H_2



Triple Point	13.8 K (-259^{o}C); 7.2 kPa
Critical Point	33.2 K (-240^{o}C); 1.3 MPa
Melting Point	14 K (-259.2^{o}C); 1 atm
Boiling Point	20 K (-253^{o}C); 1 atm



Ortho Hydrogen: 75% Abundance

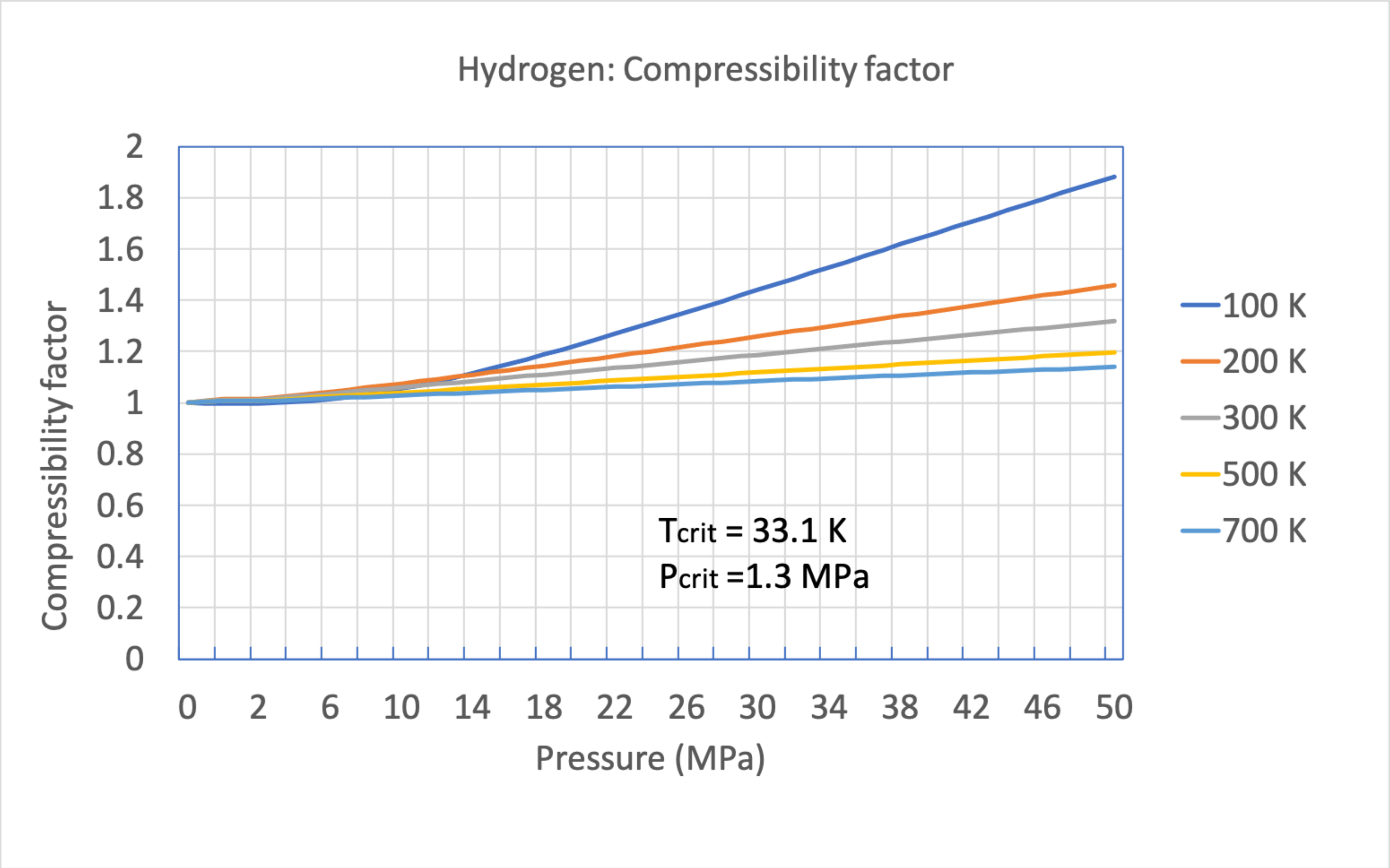


Para Hydrogen: 25% Abundance

Properties of H_2

Properties of H_2

Real Gas Equation: $PV = ZnRT$
Z: Compressibility
For Z = 1: Ideal Behaviour



Hydrogen shows Z close to 1 upto pressures of 10 MPa (100 bar)

SOURCE: https://pressbooks.bccampus.ca/thermo1/chapter/3-2-real-gas-and-compressibility-factor/

Properties of H_2

DIFFUSIVITY AND DENSITY

- **Air Diffusion; Diffusibility (cm^2/s) Values in Air:**
  - **Hydrogen: 0.63**
  - **Methane: 0.20**
  - **Gasoline Vapours: 0.08**

- **Density of Hydrogen Gas at NTP: 0.08 kg/m^3 (7% as that of air)**
- **Liquid Hydrogen Density: 70.8 kg/m^3 (7% as that of Water)**

Fuel Properties of H_2

Property	Hydrogen	Petroleum	Methanol	Methane	Propane	Ammonia
Boiling point [K]	**20.3**	350–400	337	111.7	230.8	240
Liquid density [$kg \cdot m^{-3}$] NTP	**70.8**	702	797	425	507	771
Gas density [$kg \cdot m^{-3}$] NTP	**0.0899**	—	—	0.718	2.01	0.77
Heat of vaporization [$kJ \cdot kg^{-1}$]	**444**	302	1168	577	388	1377
Higher heating value [$MJ \cdot kg^{-1}$]	**141.9**	46.7	23.3	55.5	48.9	22.5
Lower heating value [$MJ \cdot kg^{-1}$]	**120.0**	44.38	20.1	50.0	46.4	18.6
Lower heating value (liquid) [$MJ \cdot kg^{-3}$]	**8520**	31170	16020	21250	23520	14350
Diffusivity in air [$cm^2 \cdot s^{-1}$]	**0.63**	0.08	0.16	0.20	0.10	0.20
Lower flammability limit [vol% (in air)]	**4**	1	7	5	2	15
Upper flammability limit [vol% (in air)]	**75**	6	36	15	10	28
Ignition temperature in air [°C]	**585**	222	385	534	466	651
Ignition energy [mJ]	**0.02**	0.25	—	0.30	0.25	—
Flame velocity [$cm \cdot s^{-1}$]	**270**	30	—	34	38	—

Properties of H_2

ENERGY CONTENT

- **Energy Per Unit Mass:**
  - **Hydrogen: 140.4 MJ/kg**
  - **Natural Gas: 55 MJ/kg**
  - **Gasoline: 48.6 MJ/kg**

- **Energy Per Unit Volume:**
  - **Compressed Hydrogen**
    - **10 MJ/m^3 (1 bar, 15°C)**
    - **1825 MJ/m^3 (200 bar, 15°C)**
    - **4500 MJ/m^3 (690 bar, 15°C)**
  - **Liquid Hydrogen: 8491 MJ/m^3**
  - **Gasoline: 31,150 MJ/m^3**

Properties of H_2

FLAMMABILITY

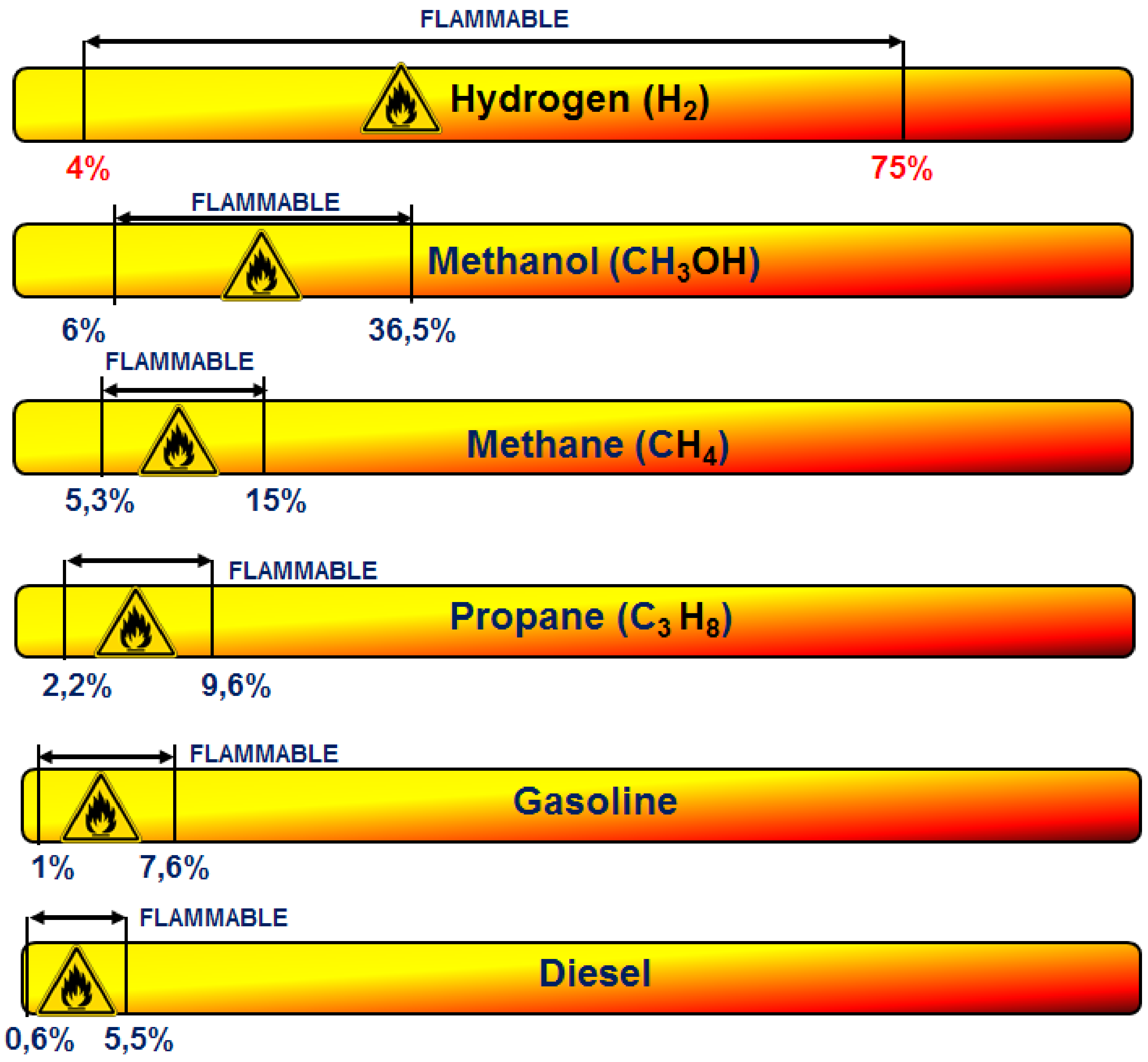
- Flammability in ambient air (volume %):
  - Hydrogen: 4 – 75%
  - Gasoline: 1 – 7.6%
  - Explosives: 15– 59%

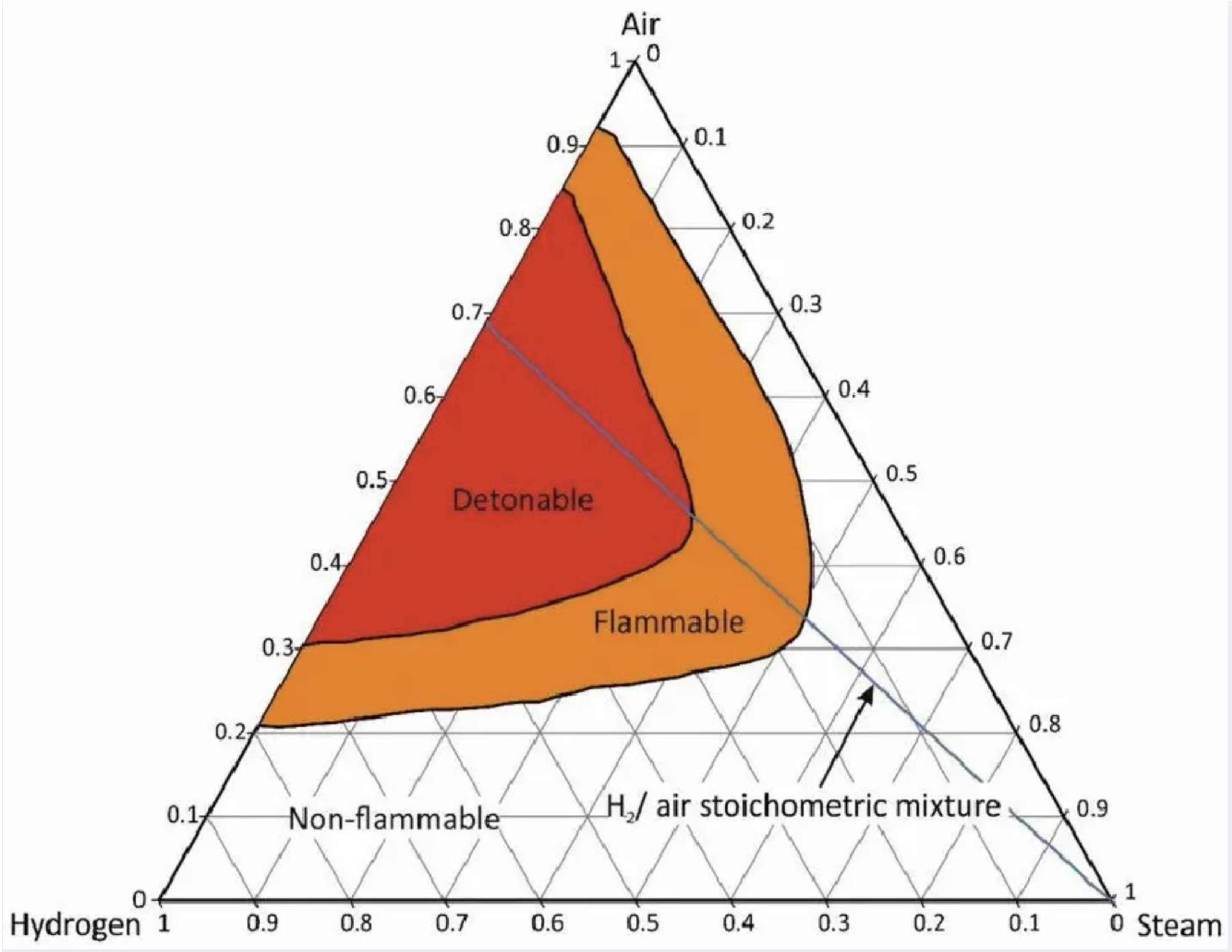
- Equivalence Ratio (ϕ): Ratio of Fuel to Oxidizer in Stoichiometric Proportions.
- Given by Mass Flow Rates of Fuel with that of Air/Oxygen
  - Hydrogen: $0.1 < \phi < 7.1$
  - Gasoline: $0.7 < \phi < 4$

- Hydrogen-fuelled IC can work stably even at dilute conditions
- Advantages:
  - Ease of Ignition/Start
  - Better Combustion
  - Better control on Engine operations and Emissions

Properties of H_2

FLAMMABILITY





Properties of H_2

IGNITION AND AUTO-IGNITION

- **Ignition Energy of Hydrogen is 0.02 mJ; of Gasoline: 0.24 mJ**
- **Prompt ignition even for leaner mixtures**
- **Hot spots or hot gases can serve as means of ignition – premature ignition and flashback**
- **Auto-ignition Temperature: Minimum temperature at which a fuel initiates a <u>self-sustained</u> combustion in a combustible mixture, in <u>absence</u> of external source of ignition**
  - **Hydrogen: 585^{o}C**
  - **Gasoline: 240 – 460^{o}C**
- **Difficult to ignite hydrogen – air mixture on basis of heat alone without some additional ignition source.**

Properties of H_2

FLAME SPEED

- Flame Speed: The rate at which the flame-front advances further when ignited

- At stoichiometric ratio:
  - Hydrogen: 3.46 m/s
  - Gasoline: 0.42 m/s

- Hydrogen engine can more closely approach the Thermodynamic cycle

Properties of H_2

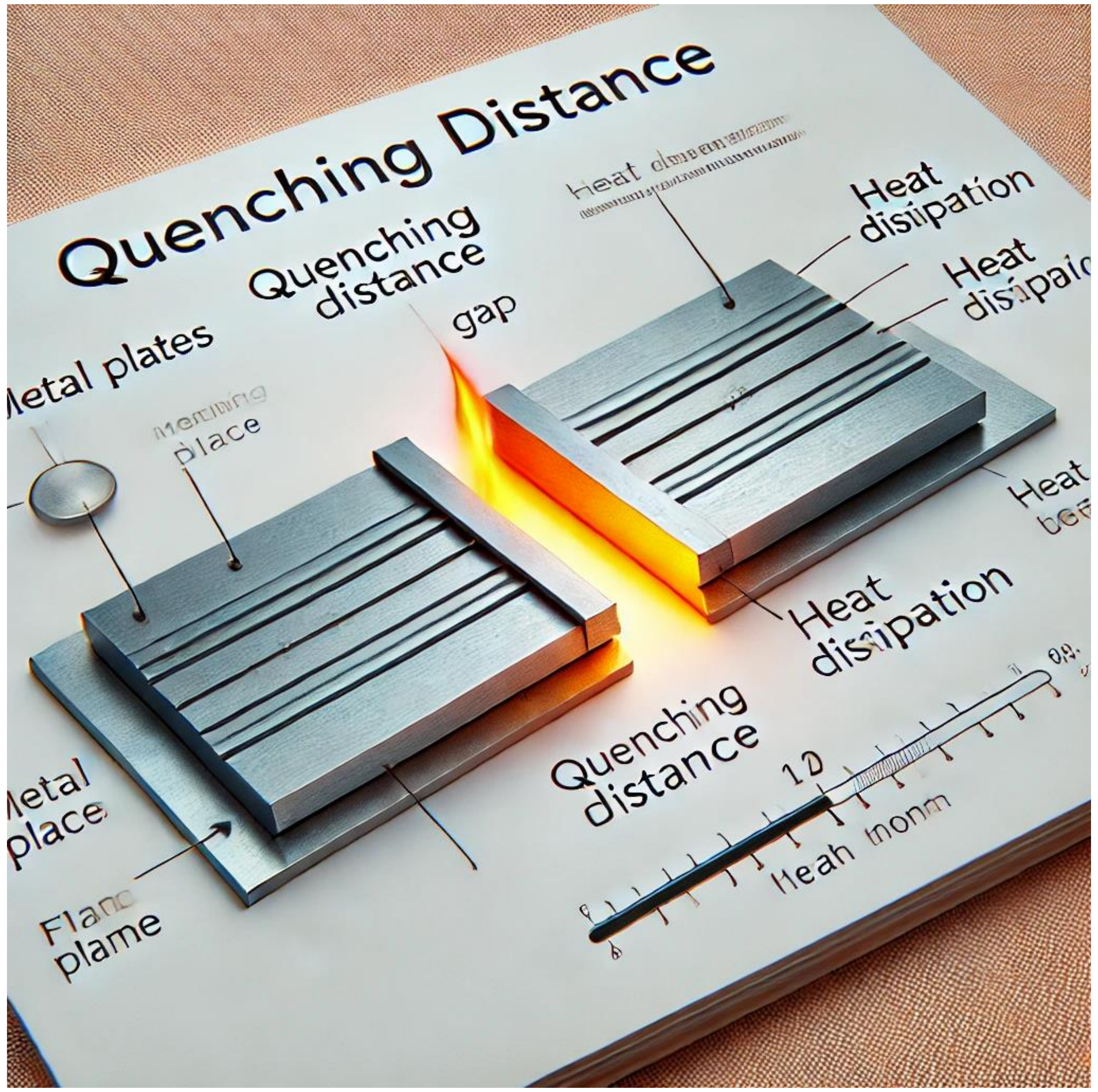
QUENCHING DISTANCE

- **Quenching Distance: Minimum distance from a parallel surface to the flame (or two parallel surfaces) at which the flame extinguishes**

- **Typically provides the idea of the point at which heat losses from the flame are greater than the heat produced in the combustion**

- **Quenching Distances:**
  - **Hydrogen: 0.64 mm**
  - **Gasoline: 2 mm**

- **Hydrogen flames are difficult to extinguish and have a tendency of back-firing**

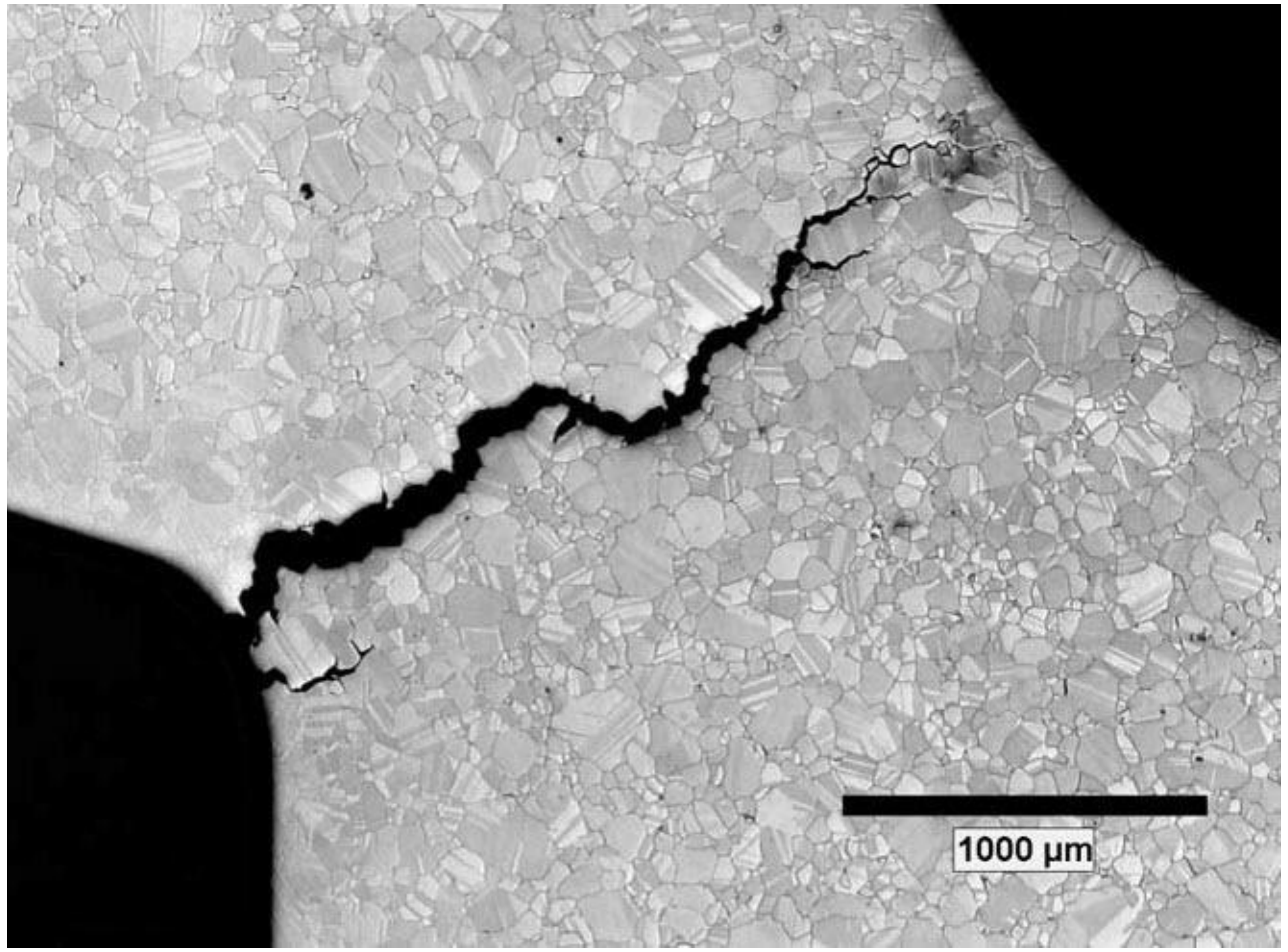


Properties of H_2

EMBRITTLEMENT AND LEAKAGES

- **Materials show embrittlement due to constant exposure to Hydrogen**
- **Affecting Factors:**
  - **Concentration of Hydrogen, Purity, Pressure, Temperature**
  - **Stress Level, Stress Rate, Tensile Strength**
  - **Grain Structure, Microstructure**
  - **Material Composition, Annealing History**

- **Leakage:**
  - **Low density and High Diffusivity of Hydrogen makes it prone to Leakages, dispersing much faster than Gasoline**
  - **Forms uniform air-hydrogen mixture**
  - **Fast dispersion also makes it diffuse to below-flammability limits in open spaces**



Source: Annuzzi et al (2017)