Beckett THERMAL SOLUTIONS
Engineering Solutions for a Better Tomorrow

Hydrogen in the US Marketplace

Prepared and Presented By Jacob Cleary
assisted by Gunther Berthold

Introduction

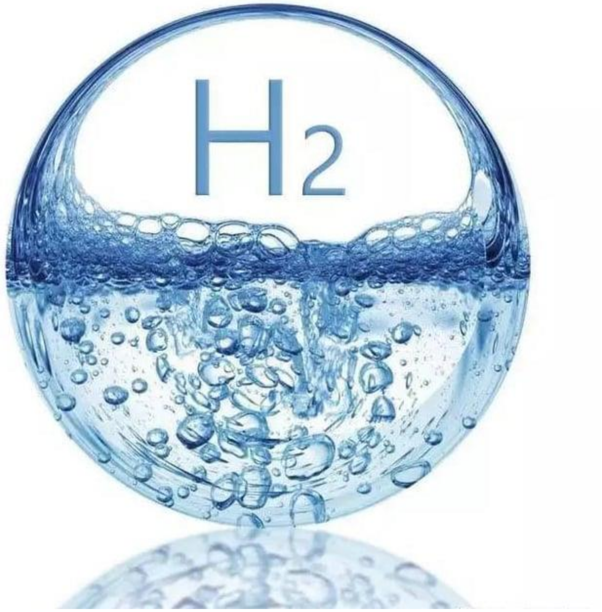
Presenter – Jacob Cleary

- Product Development Engineer
  - Beckett Thermal Solutions
- Started as a Co-op in 2016.
  - Hire full-time 2019
- Aerospace Engineering Degree
  - University of Cincinnati
- Spent 1 year in England with Beckett Derby working on Hydrogen Combustion
- Current work involved decarbonization within the gas industry.

Contents

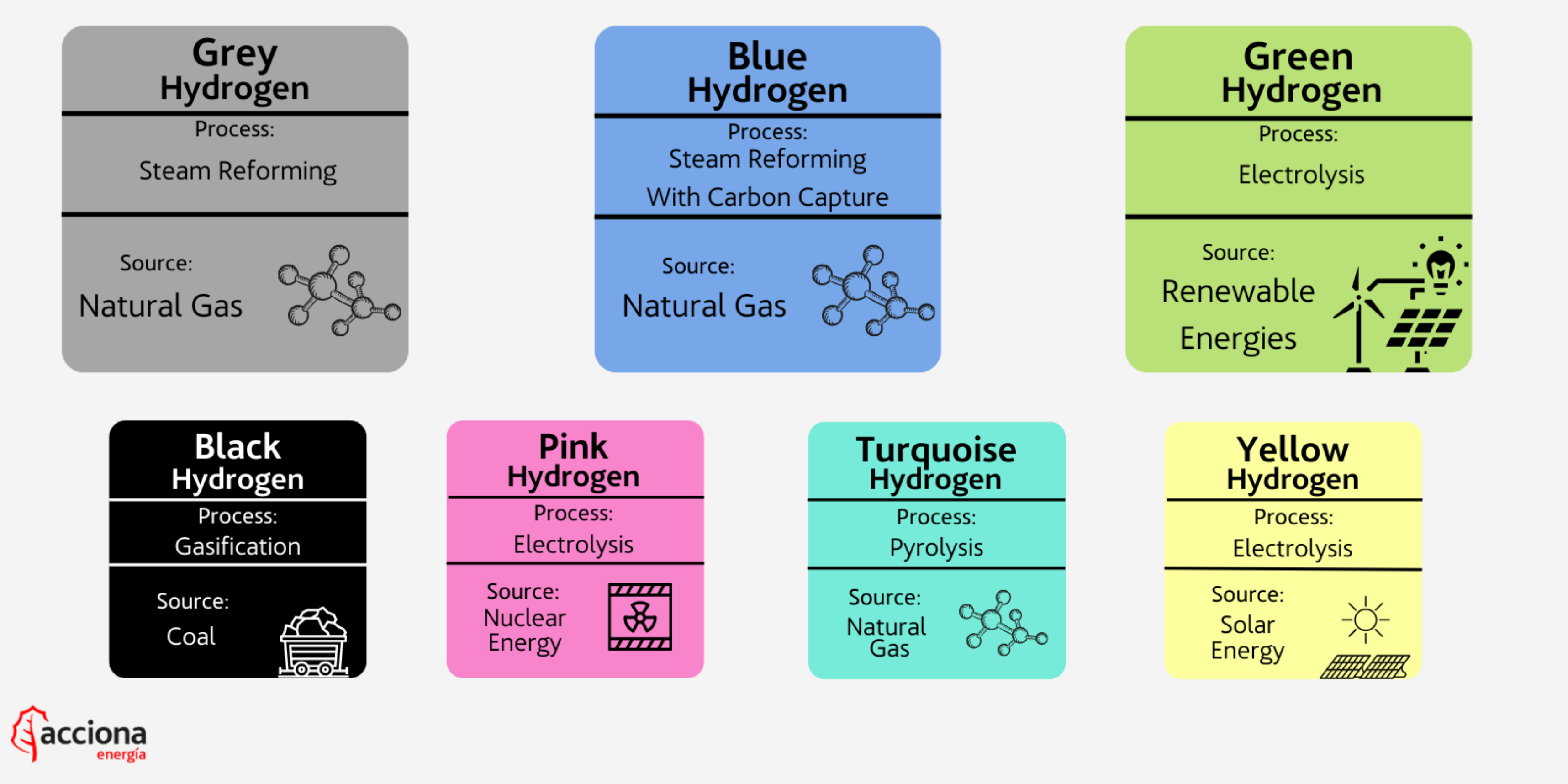
What are we talking about today?

- Part 1: European Market
  - UK
  - EU
- Part 2: US Market
  - Government Initiatives
  - US Hydrogen use sectors
- Part 3: 100% Hydrogen Combustion Technical
  - Compared to CH4
  - Flame Characteristics
  - Safety



Hydrogen Production

Colors of Hydrogen

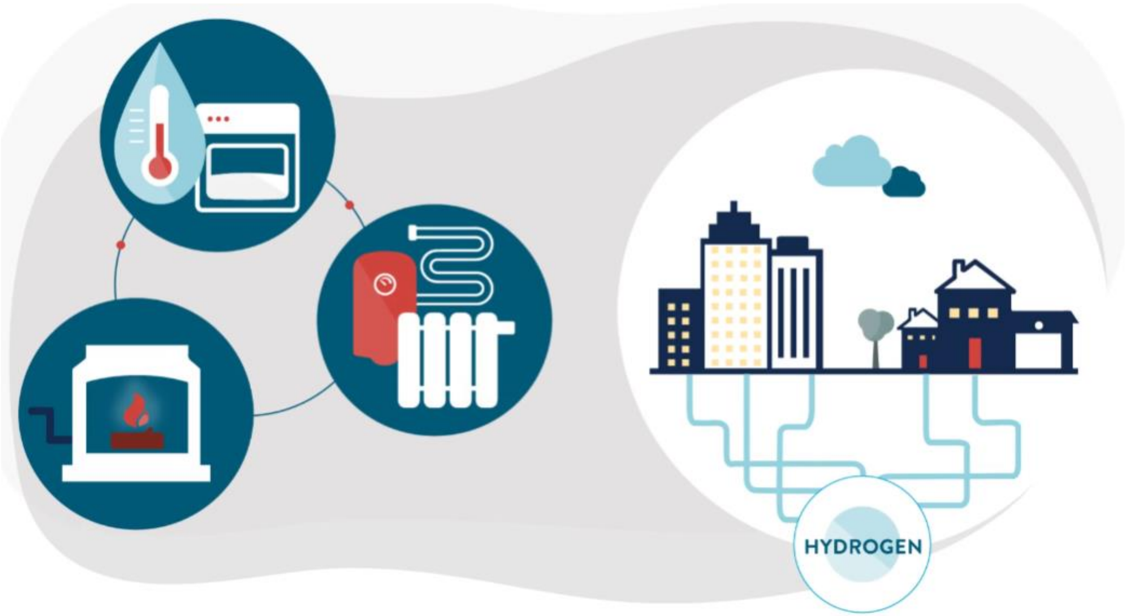


European Efforts

European Efforts

UK Hy4Heat Program (2017-2022)

- Mission: “establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This will enable the government to determine whether to proceed to community trial.”
- Focus on 10 individual Work Packages
- Developed First-of-its-Kind heating and cooking appliances for 100% hydrogen
  - Domestic Boilers, Commercial Boilers, Cooking, Fireplaces



European Efforts

UK Hy4Heat Program (2017-2022)

Hy4Heat

Company	Appliances	Certification Status	Deployments
Bosch	Combi Boiler	Field Trial Certified[1,2]	• Hydrogen Home • H21 HyStreet (Spadeadam) • COP26 • Milford Haven Energy Kingdom • Kiwa
	Regular Boiler	Field Trial Certified	
Baxi	Combi Boiler	Fully Certified[3]	• Hydrogen Home • H21 HyStreet (Spadeadam) • COP26 • Kiwa
	System Boiler	Fully Certified	
Enertek HyCookers	Hob	Fully Certified	• Hydrogen Home • COP26
	Oven & Grill		
	Freestanding Cooker		
Enertek HyFires	Standard Fire [4]	Fully Certified	• Hydrogen Home • COP26
	Glass-Fronted Balanced Flue Fire		
	Glass-Fronted Conventional Flue Fire[5]		
Clean Burner Systems	Standard Fire	Fully Certified	• COP26
	Glass-Fronted Balanced Flue Fire		
	Innovative Fire	Field Trial Tested[6]	

- Results: "(The Project has) been able to demonstrate that it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen across a wide range of appliances…"

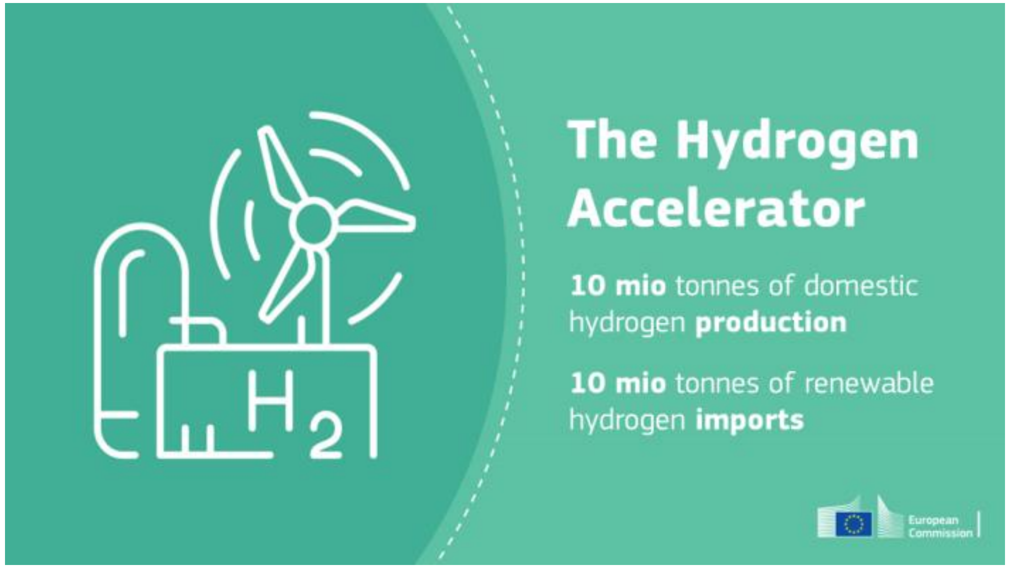
European Efforts

European Green Deal (July 2020)

- Looking at Energy System "As a Whole" across multiple systems, infrastructures, and sectors of use
- Energy Efficiency is the core of the program
- Emphasis on Electrification
  - Residential: 40% (2030), 50-70% (2050)
  - Service Sector: 65% (2030), 80%(2050)

European Efforts

European Green Deal – Hydrogen Strategy (Current)



- 20 Key Point plan implemented in July 2020, completed in 2022
- 2% of EU Energy Use was hydrogen in 2022
  - 96% of this hydrogen was Produced with Nat Gas
- By 2030, 10 million tonnes of renewable hydrogen will be created, and the same amount imported.
  - Hydrogen Accelerator Program
  - Promoted by Russian Energy Independence
- European Hydrogen Bank – March 2023
- Renewable Hydrogen Pilot Auction in Q3 2023

The Bleak Hydrogen Blending Future in Europe

- "The blending of hydrogen into the natural gas system should be a last resort solution, as it is less efficient compared to the use of **using hydrogen in its pure** form and diminishes the value of hydrogen"
  - 20% Hydrogen results in 6-7% GHG reduction at point of use.
  - Increase end user gas cost in EU on average 23.8%

Josep Borrell – EU Parliament

The Positive Future - European hydrogen projects

- 355 hydrogen projects
- 86 retrofitting/repurposing infrastructure projects
- 88 integrated projects
- Whole value chain

- 12 Home 100% Field Trial in Netherlands kicked-off Winter 2022

entsog european network of transmission system operators for gas

Start date

Project promoter

Search

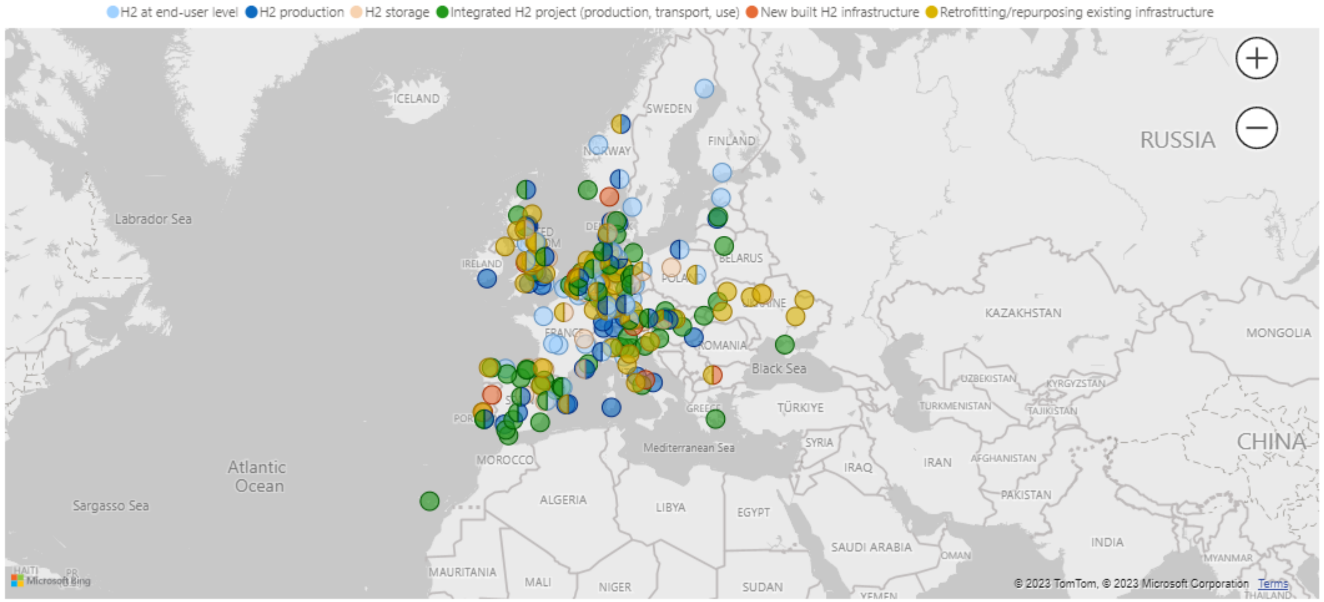
Filters

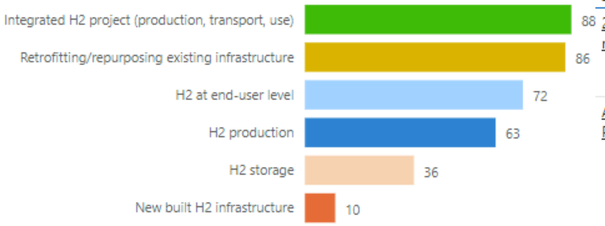
Country

Type of project

Project maturity

Start date





Project name	Project promoters	Country	Timeline	Project maturity	Scope & goal
2G's CHP fleet retrofit	2G Energy AG	Germany	NA-NA	Project	Existing natural gas CHP plants can be easily retrofitted for the operation with hydrogen by moderate costs; by this means millions of tons of CO2 can be saved each year
Aberdeen Vision Project	SGN / NG / PBDE / DNVGL	United Kingdom	NA-NA	Project	The focus for the Aberdeen Vision project is the transport and use of hydrogen produced from reformed natural gas from StFergus in North East Scotland. Outline the possibility of using advanced hydrogen production at St Fergus. And to discuss the technology and safety requirements for the transportation and storage of CO2 from hydrogen production.

https://h2-project-visualisation-platform.entsog.eu/

United States Hydrogen Ecosystem

US Drivers

Current Challenges in the US

- Evolving Energy Ecosystem
  - Decarbonization efforts
  - Natural Resource Preservation
  - Old Infrastructure
  - Regulatory concerns
  - Customer Demands

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US Hydrogen Economy

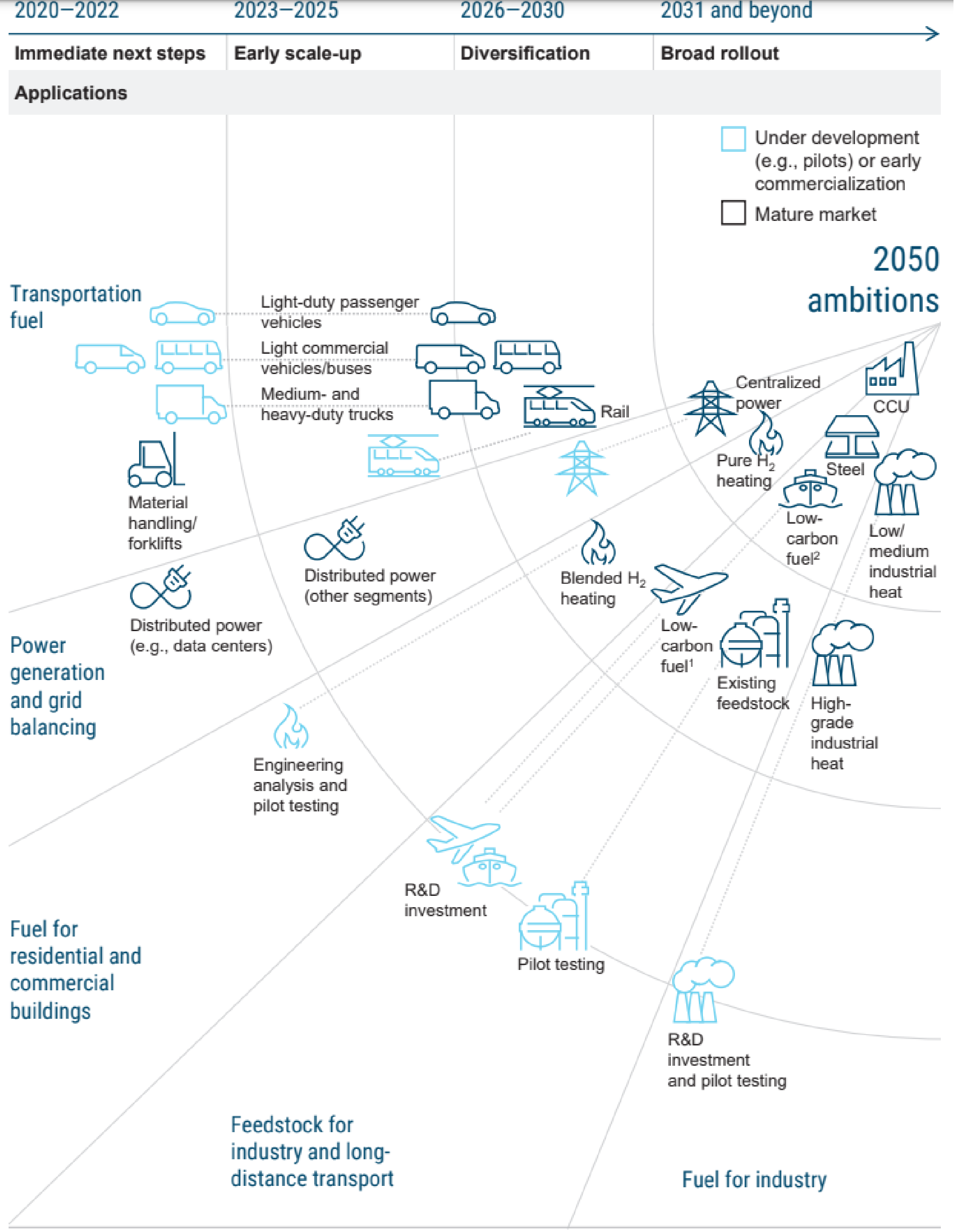
US Initiatives

- Bipartisan Infrastructure Bill
  - 9.5 Billion Dollars Allocated
    - Hydrogen Hub – 8 Billion
    - Clean Hydrogen Electrolysis – 1 Billion
    - Clean Hydrogen Manufacture and Recycle – 500 Million
- Hydrogen Earth shot
  - 1-1-1 initiative

ENERGY earthshots
U.S. DEPARTMENT OF ENERGY
Hydrogen

Application Use Cases

- Transportation
- Power Generation
- Fuel for Buildings
- Feedstock
- Fuel for Industry



1 Carbon capture and utilization (for chemicals production)
2 Biofuel, synfuel, ammonia

US Hydrogen Economy

US Hydrogen Economy

Transportation

- Accounts for 1/3rd of all Carbon Emissions (2020)
- FCEV vs BEV
  - Longer Range
  - Lower Weight
  - Smaller Powertrain
  - Fast(er) fueling times
  - Consistent Performance Across Temperature
  - Reduced Raw Material
  - Lower Emissions (Even with Gray Hydrogen
- Drawback: Limited Fueling Stations

Toyota Mirai

US Hydrogen Economy

Transportation Use Cases

- Heavy machinery and fleet trucking
- Light, medium, and heavy-duty trucks and buses
- Material handling
- Rail
- Ship

Stark Area Regional Transit Authority H2 Bus

US Hydrogen Economy

Power Generation

- Low-carbon power grid
- Long-term storage capabilities
  - Hydrogen as a battery
- Dispatchable/off grid back up
  - Fuel Cell replacing generators
  - Data centers use 40GW of backup power
- Reduced transmission loses compared to electricity

ECO-GH2 Fuel Cell and Linde Genie Cylinder

world's largest single-train ammonia synthesis loop in Texas City, TX.

US Hydrogen Economy

Feedstock or Reactant

- Ammonia and petroleum refining
- Accounts for 95% of current H2 use in the United States
    - 11 million metric tons
- Current production of this hydrogen is grey (Steam Reforming. No Carbon Capture)
- Making switch to Low Carbon Hydrogen is the path forward

World's Largest Single-train Ammonia Synthesis loop In Texas City, TX.

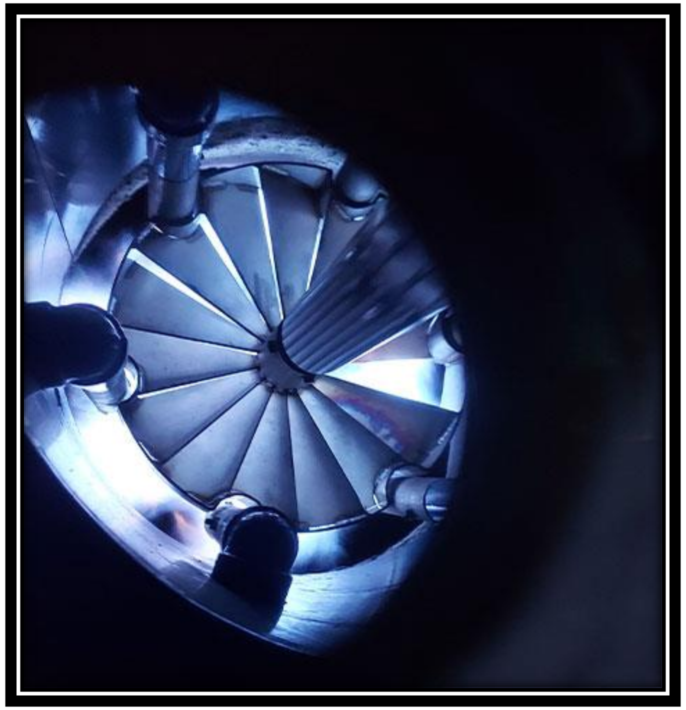
US Hydrogen Economy

Fuel for Industry (Industrial Heating)

- Milling
  - Paper mills, pulp mills, corn milling, starch, corn gluten feed, corn meal, corn oil.
  - Iron and Steel
- Chemical Manufacturing
  - Ethly alcohol, petrochemical
- Mining
  - Limestone, cement

10%

of US Carbon Emissions



Preferred Utilities MFG Corporation

Hydrogen as a Combustible Fuel

Basics of Hydrogen Combustion

	Unit	H2	CH4
GCV	kWh/m^3	3.54	11.24
NCV	kWh/m^3	2.995	10.13
Lower Wobbe	kWh/m^3	11.359	13.37
Higher Wobbe	kWh/m^3	13.427	14.82
Rel. density	[-]	0.0695	0.0575
Lower ignition limit	Vol.-%	4.1	4
Higher ignition limit	Vol.%	75	15
Air requirement	m^3/m^3	2.38	9.71
Ignition temperature	°C	510	537
Ignition delay time	ms	0.04613	46.16
Min. ignition energy	mJ	0.017	0.30
Flame velocity	cm/s	200	38.39
Flame temperature	°C	2100	1950
Diffusion coefficient	m^2/s	6.84*10^-5	1.9*10^-5
Quenching distance	mm	0.64	2.4

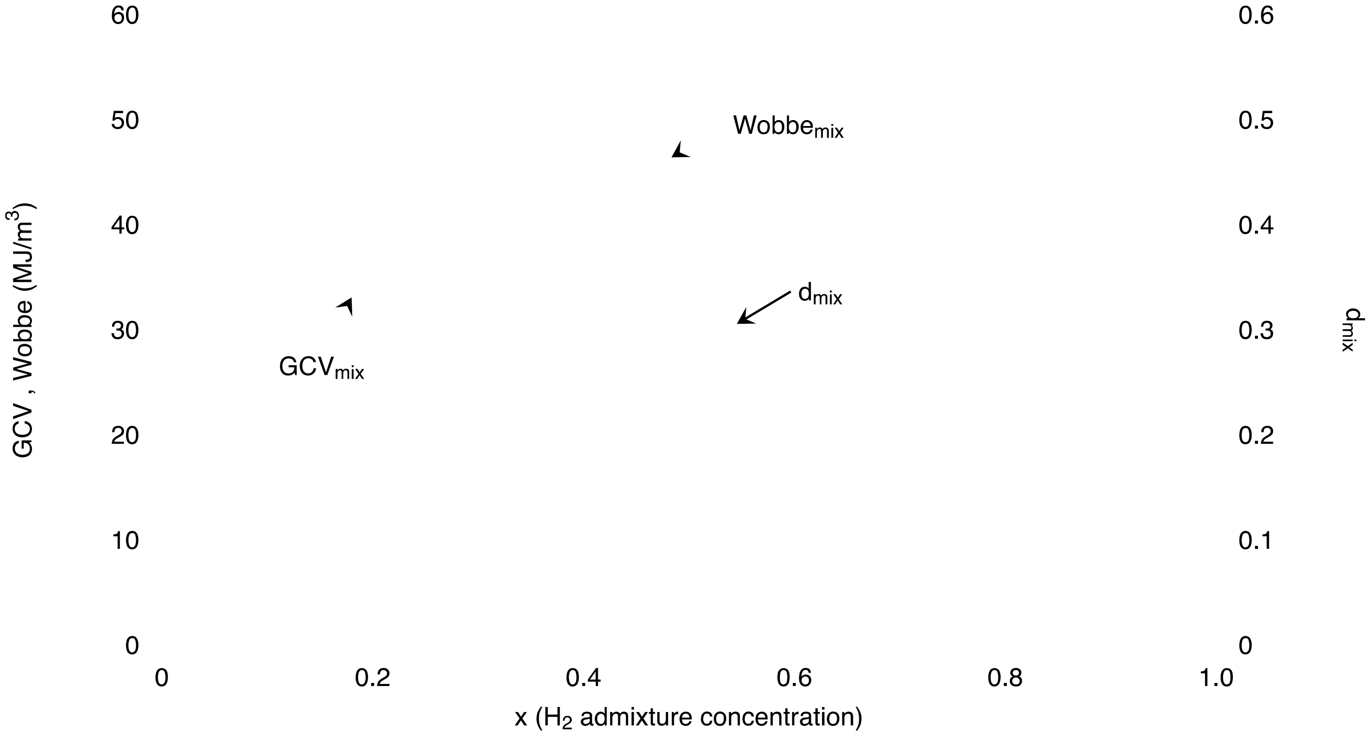
Risk Assessment

- Similar Wobbe
  - H2 Slightly Lower
- Higher flame speed (7 times compared to CH4)
  - Deflagration -> detonation
  - Flashback
  - Increased flame stability
- Ignition behaviour
  - Widening of ignition limit
  - Ignition temperature similar
- Very different min. ignition energy
  - Electrostatic discharge, metal slashing blower wheel, etc
- Combination of high reactivity, wider ignition limits and lower ignition energy needs care
- Ignition delay time 1/1000
  - Relevant for small mixture %
- Flame detection (sensors :UV or temp, no ionisation)
- Heat transfer : only convection, no radiation

Basics of Hydrogen Combustion

The Basics on H2 / NG admixtures Characteristics (4)

- Relative density: *d* = $\frac{\rho_{n,fuel}}{\rho_{n,air}}$
  - $d_{mix} = (1-x)d_{CH_4} + x\, d_{H_2}$
- GCV: gross calorific value in volumetric terms
  - $GCV_{mix} = (1-x)GCV_{CH_4} + x\, GCV_{H_2}$
- Wobbe Index (superior): *WI* = $\frac{GCV}{\sqrt{d}}$
  - $Wobbe_{mix} = \frac{GCV_{mix}}{\sqrt{d_{mix}}}$
  - The **Wobbe Index** expresses fuel **interchangeability**. Two gases with the same WI will release same amount of heat (**const = p, const = nozzle diameter**)
  - These assumptions are usually valid for residential appliances

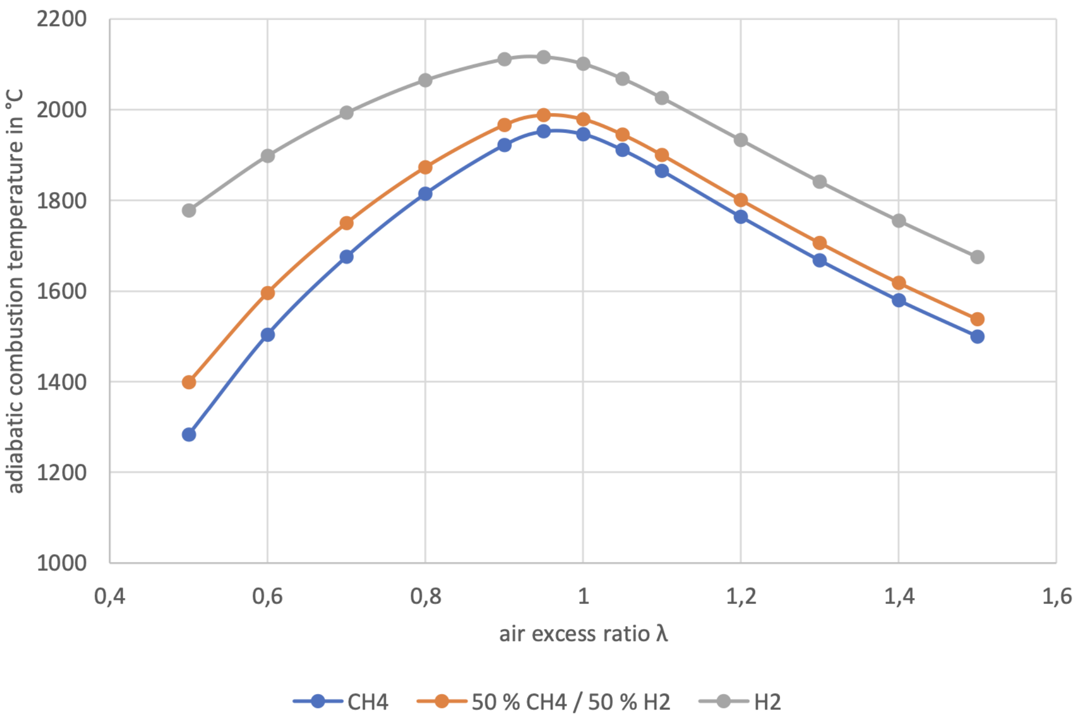


$\Delta d \approx -87.5\%$ $\Delta GCV \approx -67.9\%$ $\Delta WI \approx 9.5\%$

Basics of Hydrogen Combustion

Adiabatic flame temperature (2) (@15°C,patm=1bar)

- $\Delta T_{adiabatic} = 150°C \ or \ 302°F$
- $\Delta T_{adiabatic}$ **is only dependent on**
  - composition of fuel and oxidizer,
  - @ standard conditions



Basics of Hydrogen Combustion

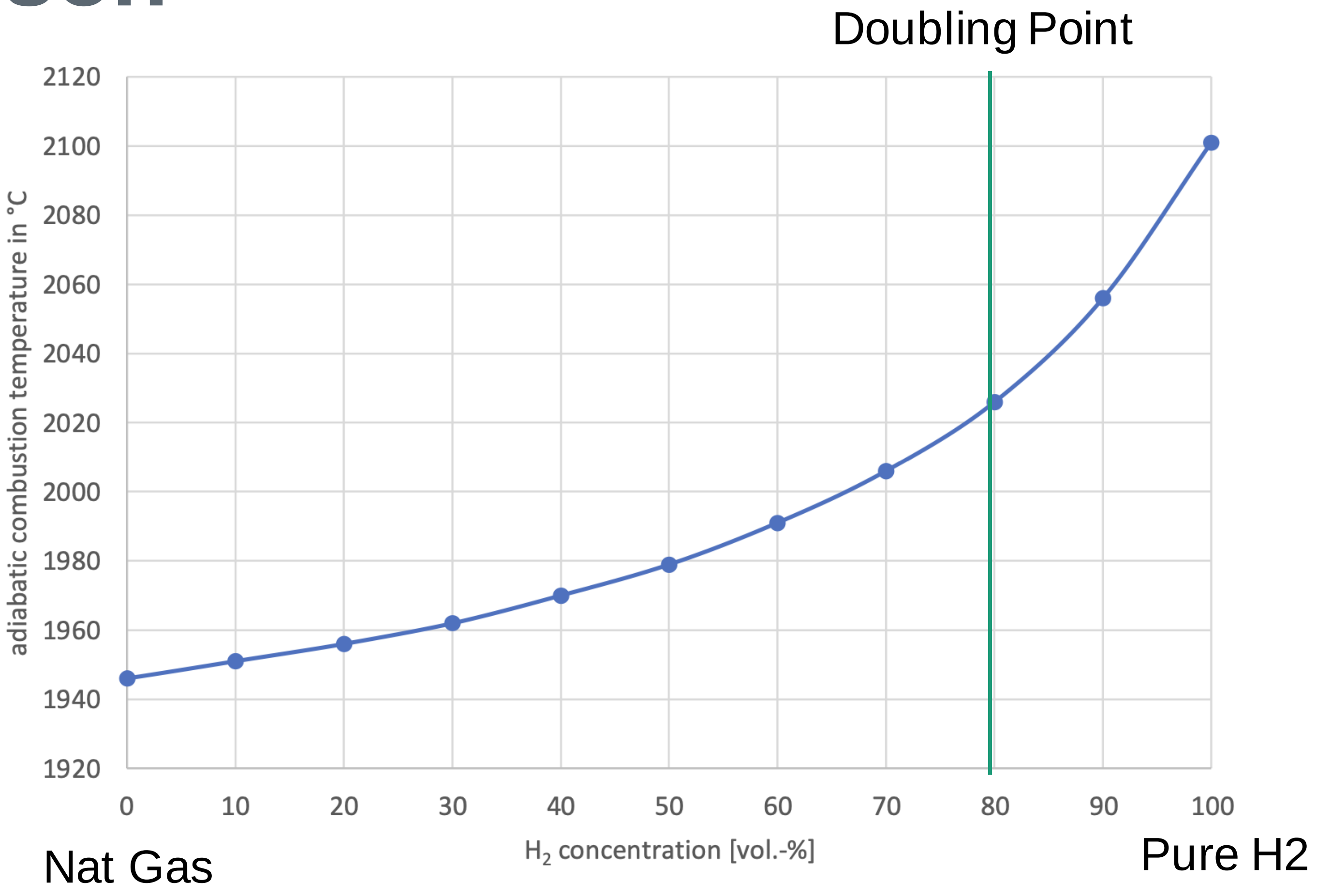
NOx Formation comparison

- Thermal NOx is a function of flame temperature
  - Exponential increase
  - Dramatic rise after 1530C
- NOx rate doubles every 90K/C after 1927C

https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node210.htm

Reminder

H2	=	2100 C
CH4	=	1950C



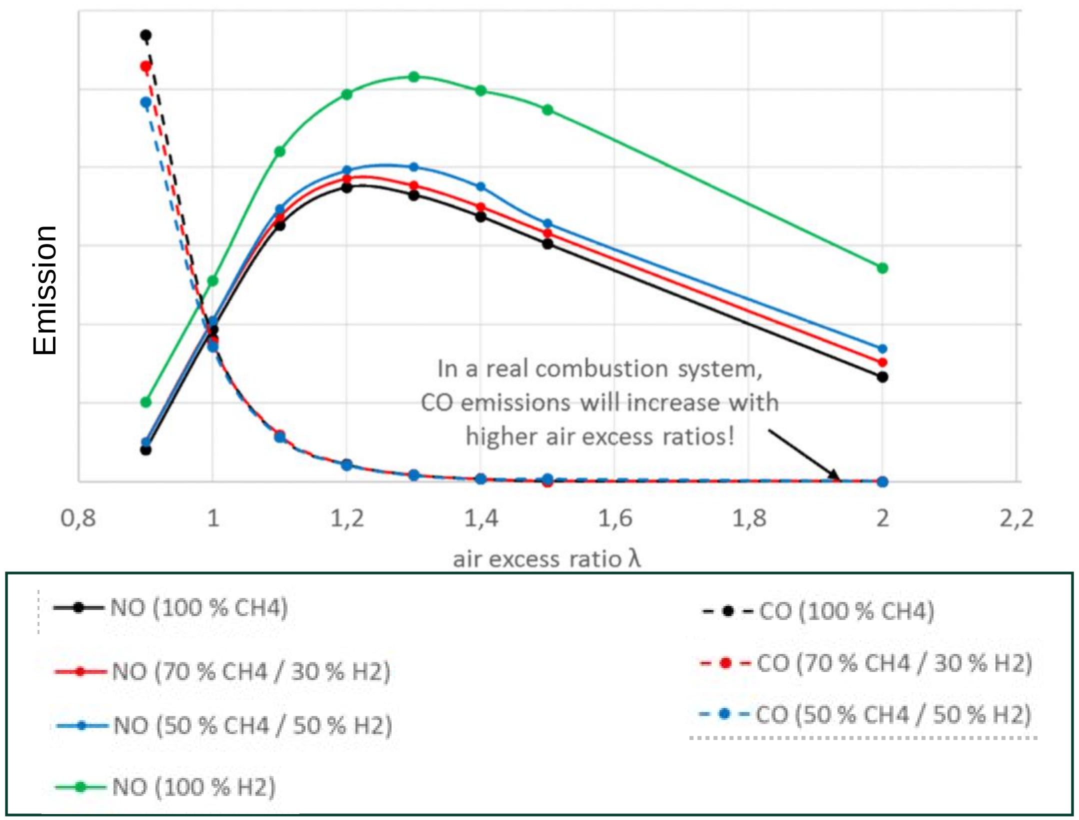
Basics of Hydrogen Combustion

NOx and CO emissions (2)

- **With increasing H2 concentration at a given λ**
  - the NO_x values increase
  - the CO values decrease

- **Attention**
  - in pneumatic systems lambda is increasing and thus NOX is decreasing

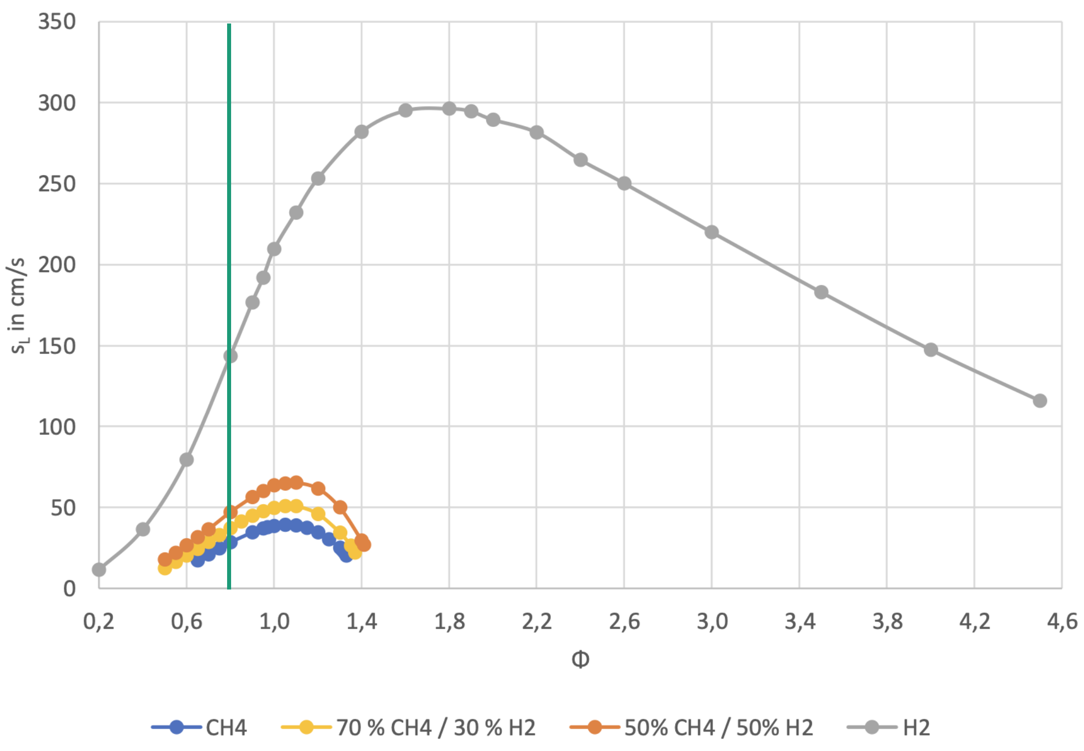
- **100% hydrogen appliances work at typically higher air fuel ratio λ. Allowing NO_x emission to be low**



Basics of Hydrogen Combustion

Laminar combustion velocities (2)

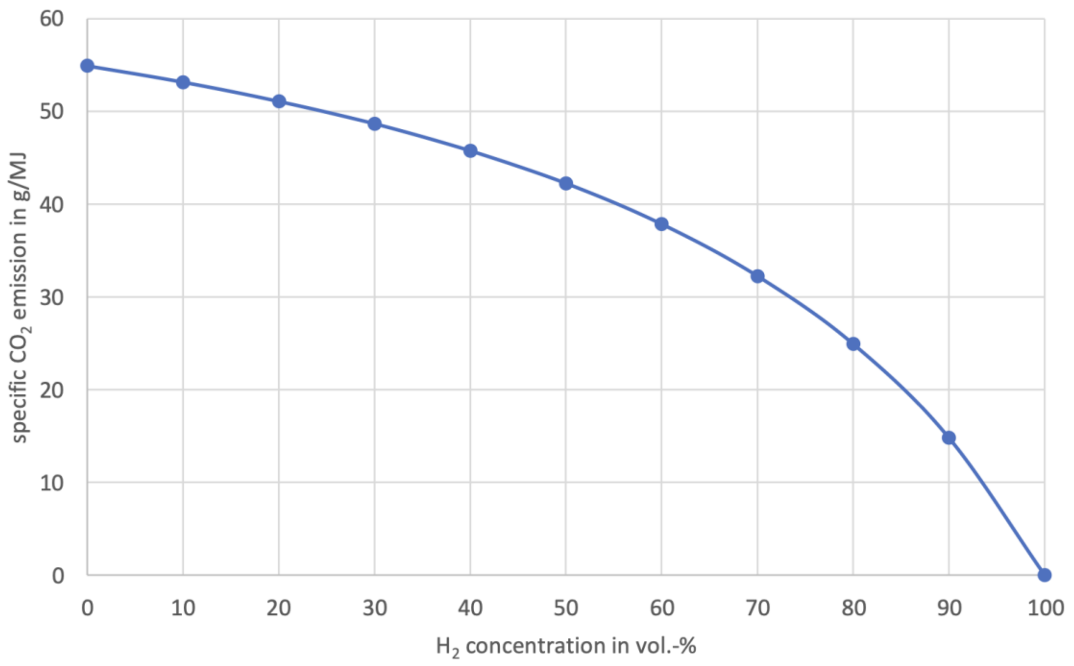
- The **laminar combustion velocity** $\boldsymbol{s_l}$ indicates how fast a flame front will propagate into a resting fuel/air mixture
- **Flame stabilization** strongly dependent on s_l
- s_l depends on composition of fuel and oxidizer, mixture temperature, pressure and $\text{fuel air ratio } \phi = {}^{1}/_{\lambda}$



Basics of Hydrogen Combustion

CO2 reduction in H2 admixture (2)

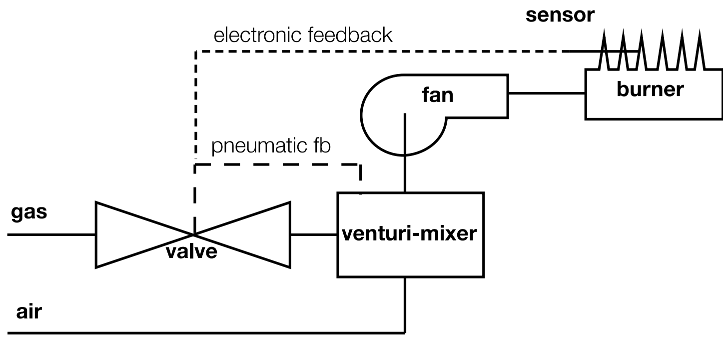
- The reduction in CO2 emissions is not linear with increasing H2 percentage
- At admixtures lower 30% the CO2 reduction is about 1/3 of the H2 concentration
- Zero carbon emissions at 100% hydrogen



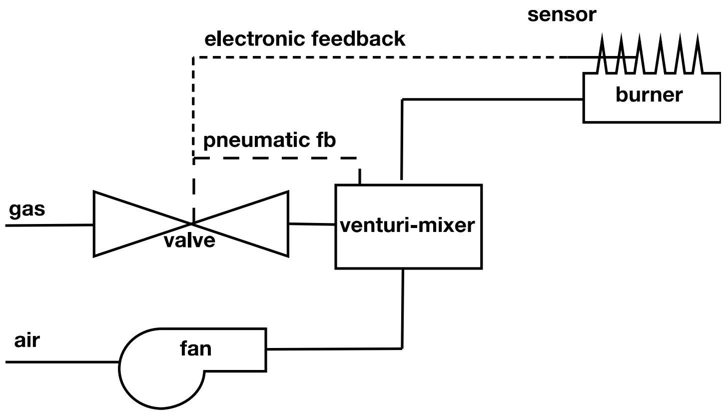
$$a\,CH_4 + b\,H_2 + x\,\lambda\,O_2 + x\,3.76\,\lambda\,N_2 \;{-}{-}{-}{-}{>}\; a\,CO_2 + (2a + b)\,H_2O + x\,(\lambda - 1)\,O_2 + x\,3.76\,\lambda\,N_2$$

Basics of Hydrogen Combustion

Pre fan mix



Post fan mix

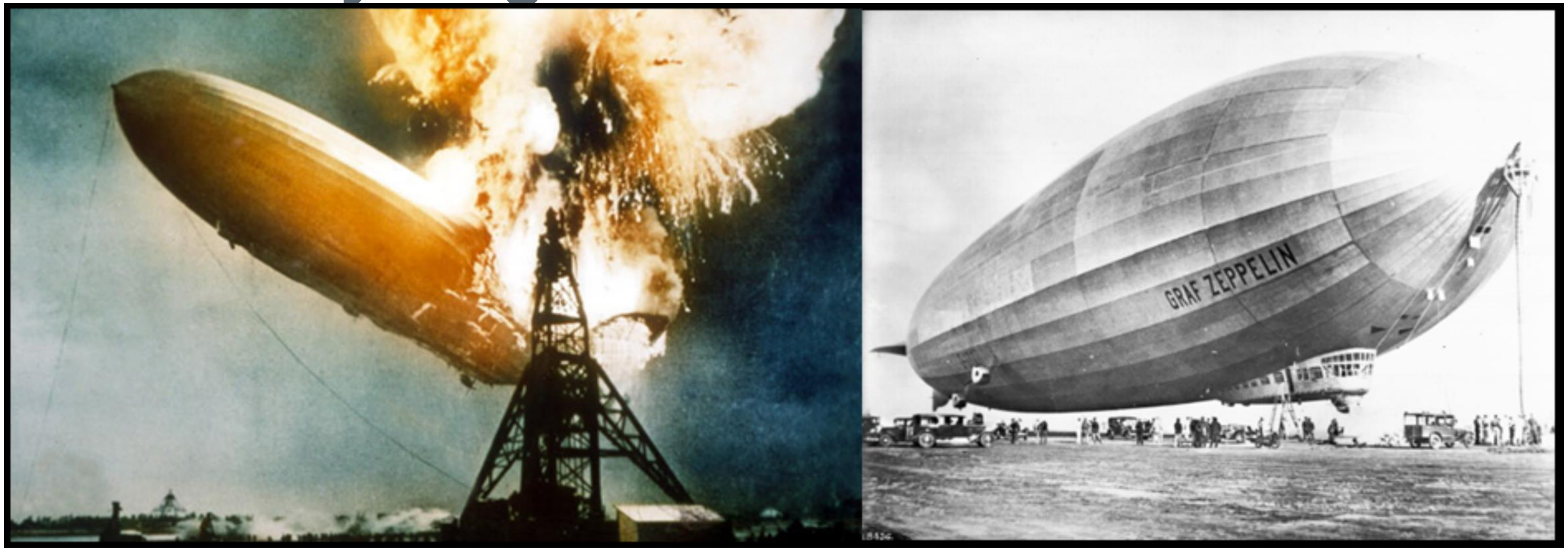


Mixing and sensing system(4)

- **Sensor**
  - Flame safety , gas adaptive system
  - Temperature, UV, pressure [Pneumatic or transducer]
- **0-30% H2 admixture**
  - Mostly pre fan mix
  - Same burner design as for NG
- **100% H2**
  - Both pre and post fan
  - Post fan reduces flashback damage risk
  - Minimizes volume of combustible mixture

Hydrogen Safety Parameters

How Safe is Hydrogen as a fuel?



- Hydrogen has a built in Safety Feature: It's ability to rapidly dissipate
- Hydrogen has a bad rap of being dangerous. But so is Natural gas... When used incorrectly.

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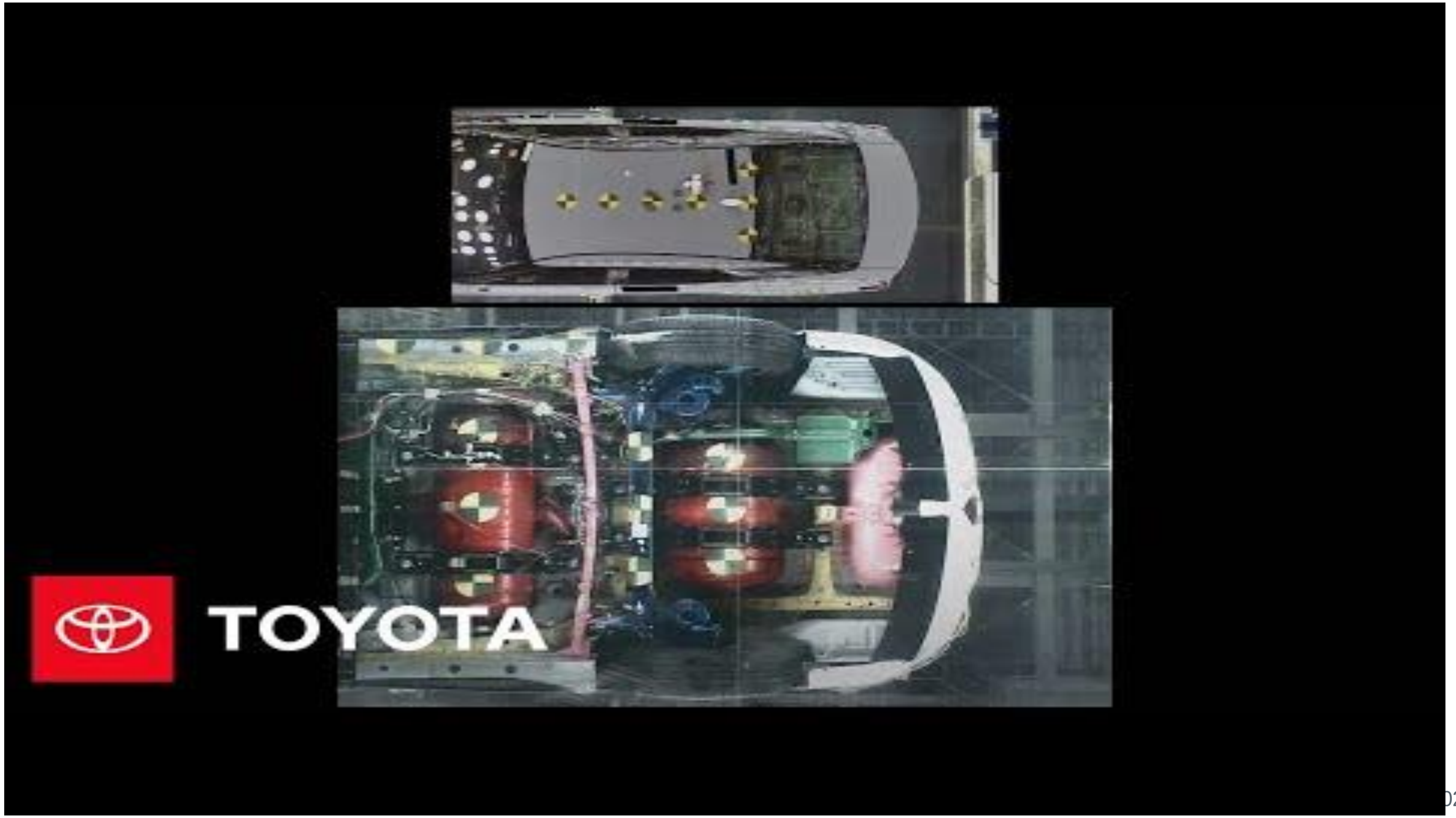
Hydrogen Safety

Every Hydrogen use case danger can be designed out

- Hydrogen dissipates in free air at 20mph vertically.
    - Leaks Dissipate past UEL very quickly and will be hard to ignite.
- Labs are designed with ample ventilation at the top of the lab.
- Post Fan Mixing to limit flashback damage.
- Odorants will be mixed to account for being an odorless gas.

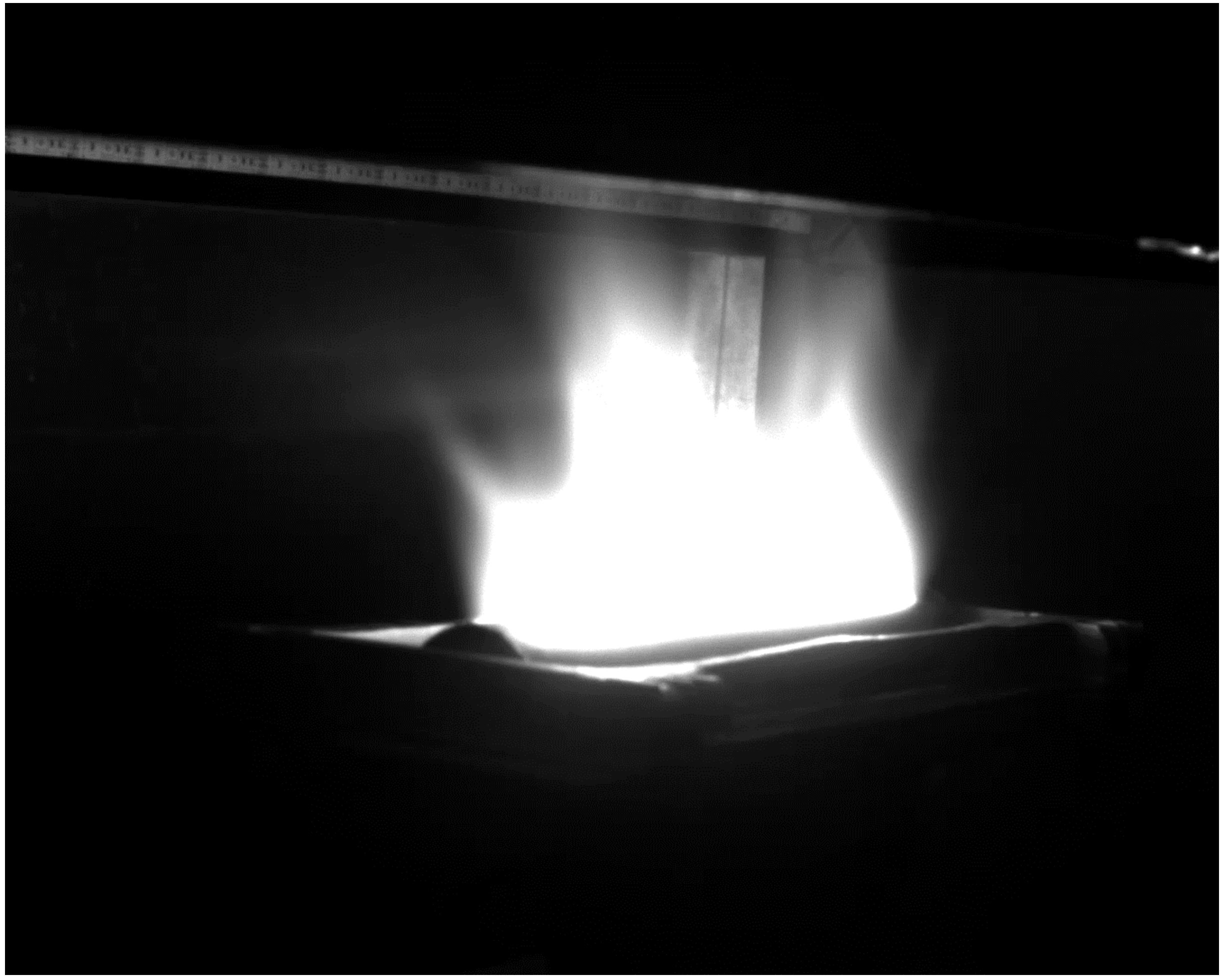
What About Tanks?

What About Tanks?

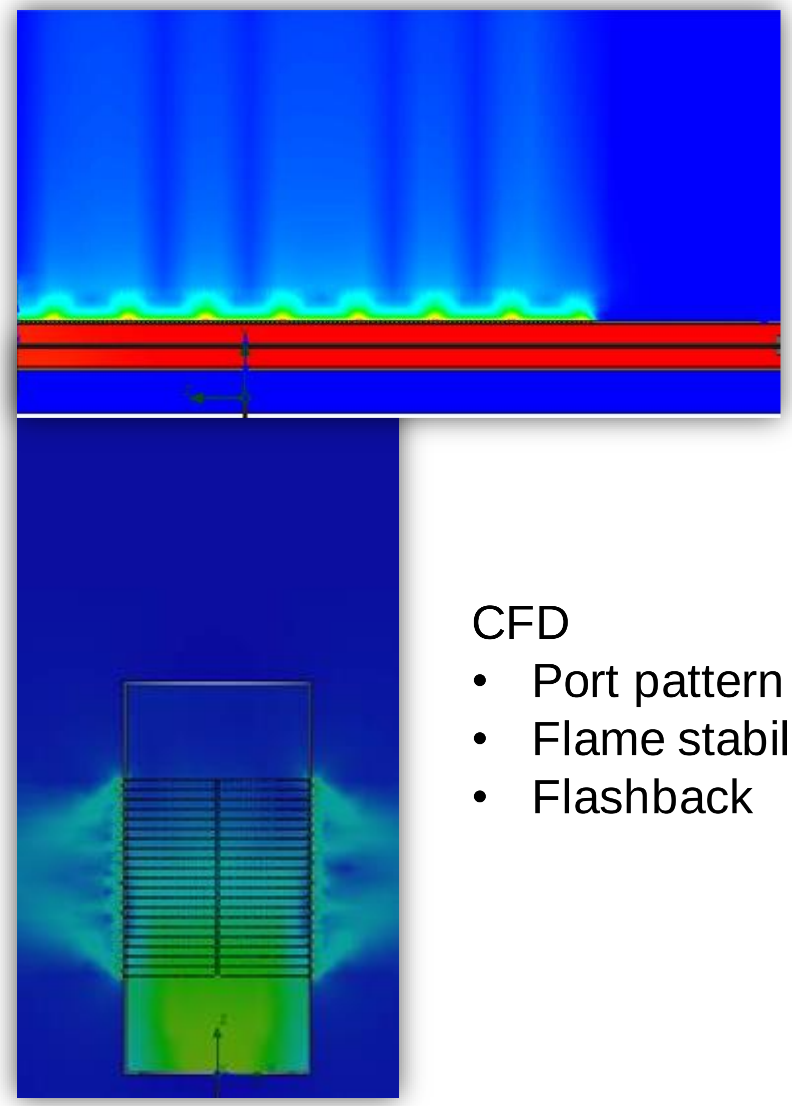


Flashback boundary layer captured with a UV camera.

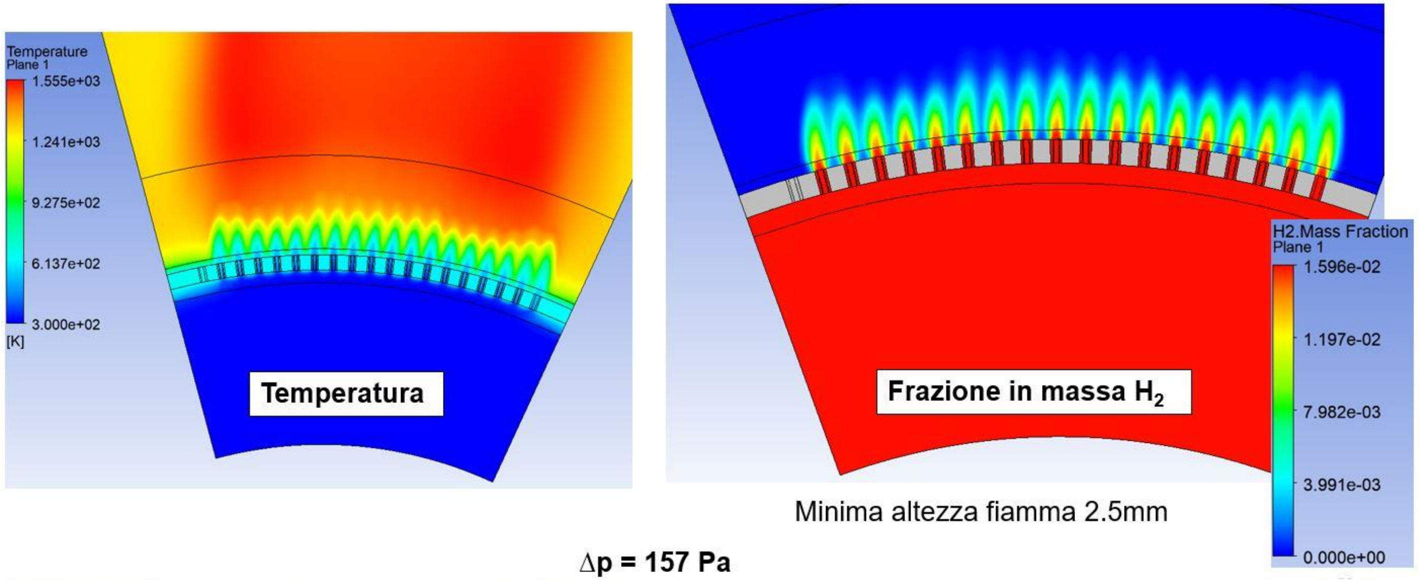
(I have an alternative Video Showing Full System FlashBack)



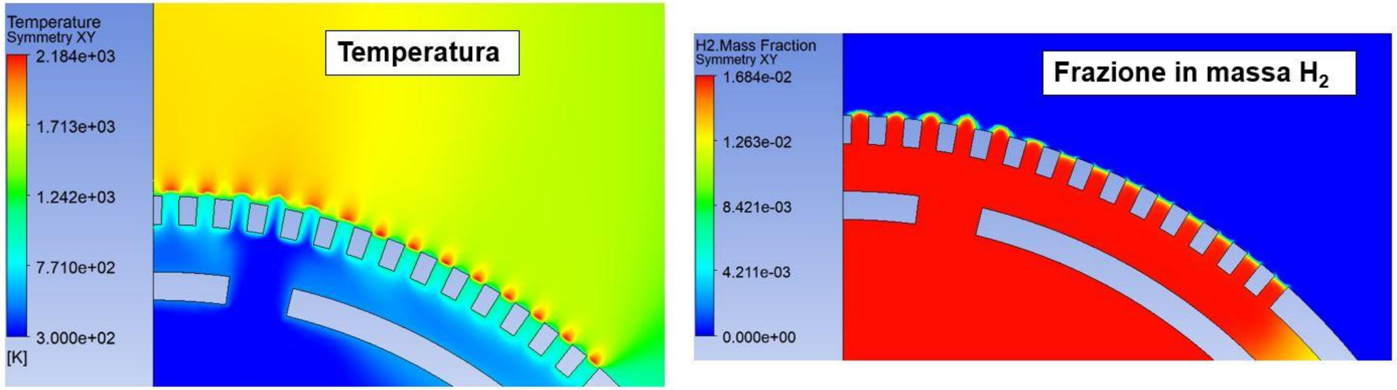
H_2 100% - CFD



CFD
- Port pattern
- Flame stability
- Flashback



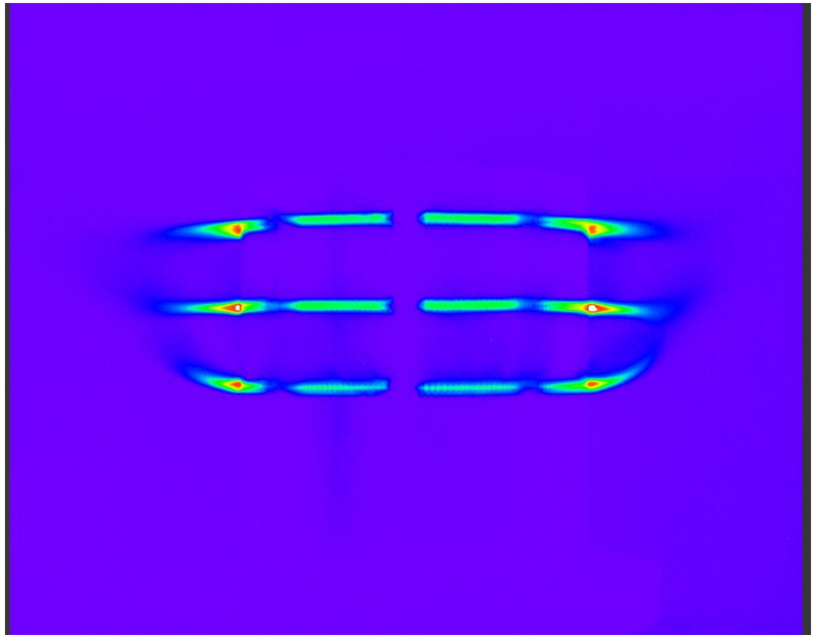
Δp = 157 Pa



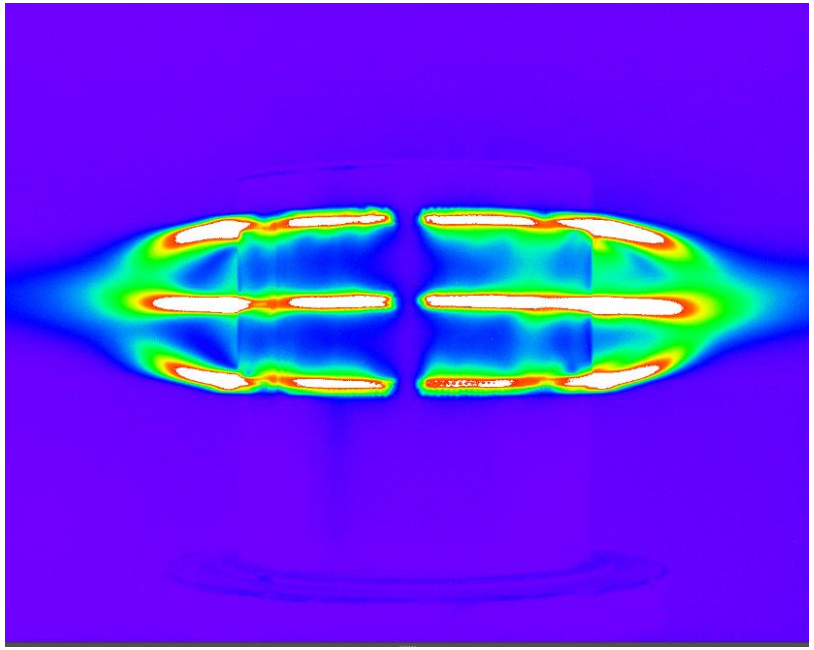
Δp = 31 Pa

H_2 100% UV Imaging

5kW λ - 1.6



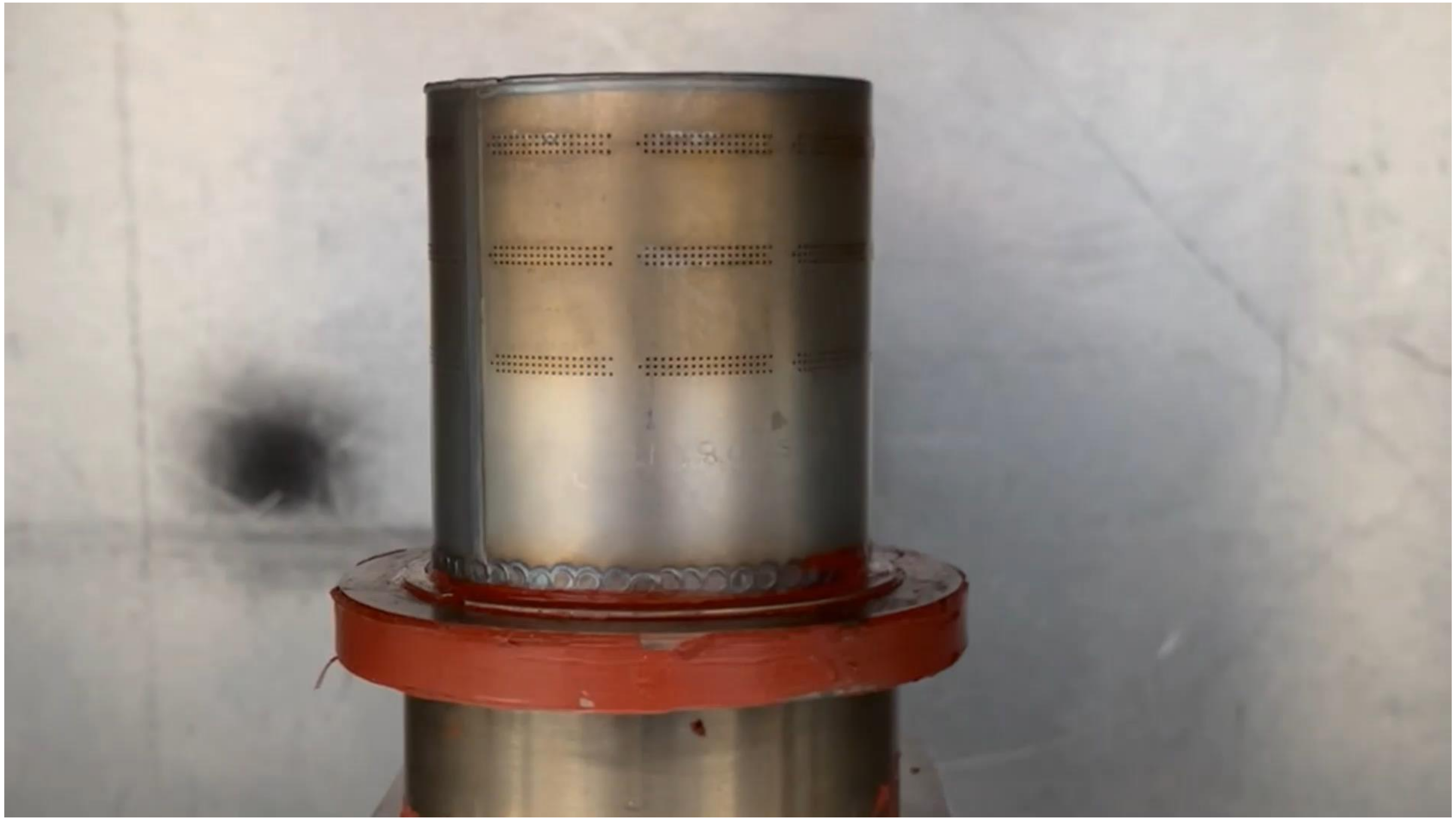
24 kW λ - 1.3



100% Hydrogen

5KW = 17060 BTU/hr

24KW = 81,888 BTU/hr



Questions?

Appendix

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European Efforts

UK 10 Point Plan (November 2020)

Point 1
Advancing Offshore Wind

Point 2
Driving the Growth of Low Carbon Hydrogen

Point 3
Delivering New and Advanced Nuclear Power

Point 4
Accelerating the Shift to Zero Emission Vehicles

Point 5
Green Public Transport, Cycling and Walking

Point 6
Jet Zero and Green Ships

Point 7
Greener Buildings

Point 8
Investing in Carbon Capture, Usage and Storage

Point 9
Protecting Our Natural Environment

Point 10
Green Finance and Innovation

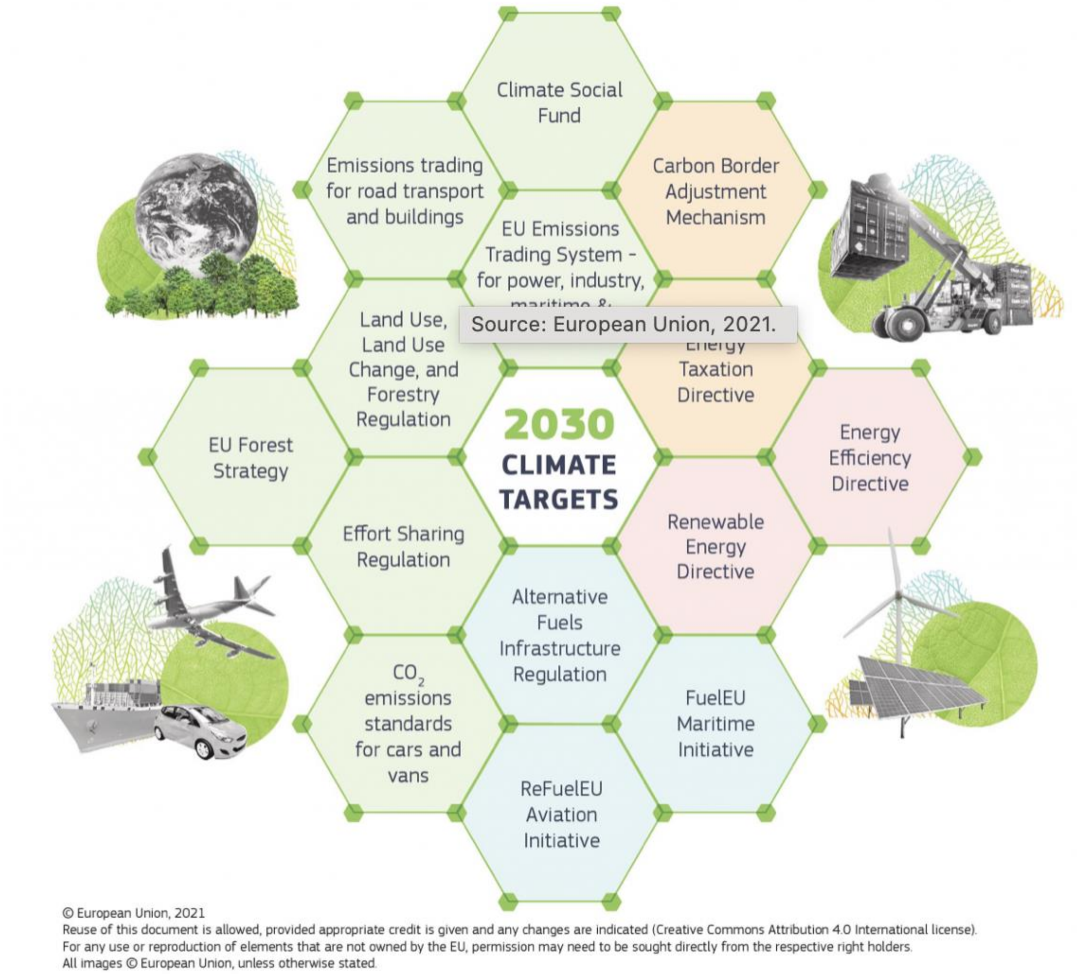
Point 2

- 5GW by 2030 goal
- Introduce a hydrogen blend to reduce emissions by 7%
- Support 100,000 Jobs by 2050

European Efforts

Fit for 55

- Policies for reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990)
- Demand & production of renewable and low carbon gases including hydrogen
- **Emission Trading System** (ETS)
  - Puts a price on carbon (24-113 EUR/kg of CO2 emission in 2021)
- **Renewable Energy Directive** (RED)
  - Target to produce 40% of EU energy from renewable sources by 2030.
- **Energy Efficiency Directive** (EED)
  - Set annual target for reducing energy use at EU level
  - Requiring average emissions of new cars to come down
    - by 55% from 2030 and 100% from 2035
    - Charging / fueling station: electric (60km) - hydrogen (150km)
- Alternative Fuel Infastruture (Inc. H2) agreed on Mar. 2023

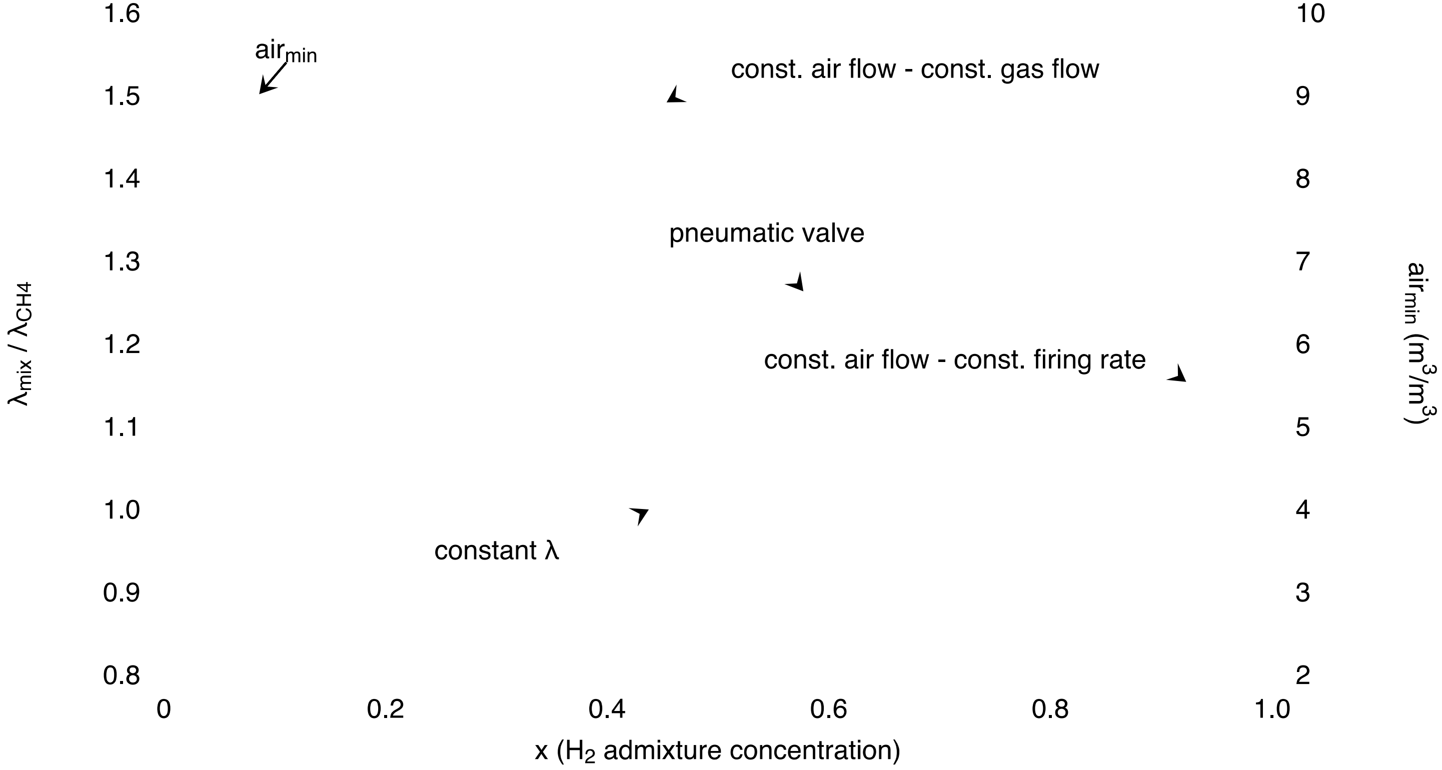


Source: European Union, 2021.

Basics of Hydrogen Combustion

λ variation with different combustion controls in H2 admixtures (4)

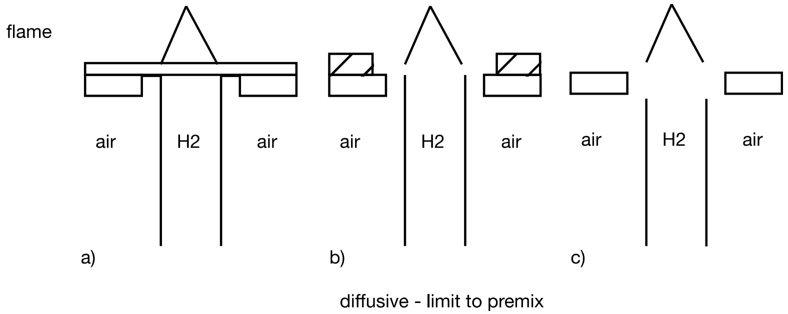
- **Pneumatic systems (air flow = const. ; p = const.)**
  - $\lambda_{mix} = \frac{air_{min,CH4}}{air_{min,mix}} \sqrt{\frac{d_{mix}}{d_{CH4}}}\, \lambda_{CH4}$
- **Combustion control systems**
  - $\lambda_{mix} = \lambda_{CH4}$
- **Air flow = const. ; gas flow = const.**
  - $\lambda_{mix} = \frac{air_{min,CH4}}{air_{min,mix}}\, \lambda_{CH4}$
- **Air flow = const. ; firing rate = const.**
  - $\lambda_{mix} = \frac{air_{min,CH4}}{air_{min,mix}} \frac{H_{i,mix}}{H_{i,CH4}}\, \lambda_{CH4}$



Basics of Hydrogen Combustion

Burner technology for hydrogen admixture (0-100%) (4)

Diffusive flame



Premix flame

Quenching distance

- CH4: $\delta = 2.4\ mm$
- H2: $\delta = 0.64\ mm$

Auto ignition temperature

- CH4: $T = 537\ °C$
- H2: $T = 510\ °C$

Minimum ignition energy

- CH4: $E = 0.3\ mJ$
- H2: $E = 0.017\ mJ$

Flammability limit

- CH4: $LFL - UFL\ (vol.\%)\quad 5.3 - 15$
- H2: $LFL - UFL\ (vol.\%)\quad 4.1 - 75$

Stability diagram – typical for 100% H2 (4)

- Tool to define working range for gas combustion burner

- Operational working range defined by Q_{min}, Q_{max}, λ_{min}, λ_{max}

  - Left / bottom corner: limit to flashback
  - Right / bottom corner: lift off

- Typical lambda values for 100% H2
  - λ_{min}=1.1 , λ_{max}= 1.9, λ_{nom}= 1.3-1.4