Hydrogen as aviation fuel - Workshop 2023
Aircraft Certification
Fire and Explosion challenges

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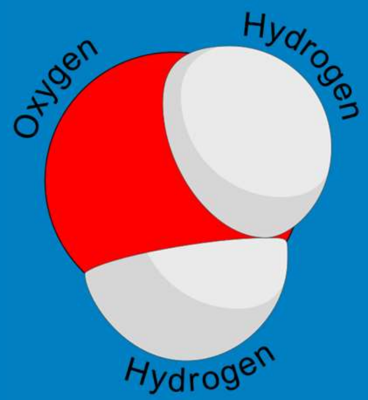
EASA Certification Directorate



Cologne, 12 June 2023

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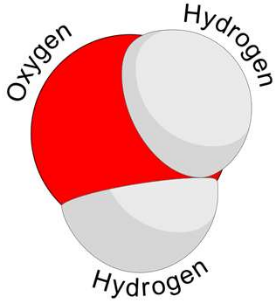
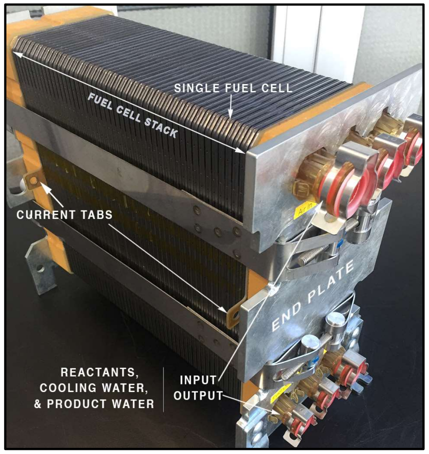
H2 Challenges

Hydrogen, a new substance on board

- With the need and wish for more sustainable flying, Hydrogen is considered to be a very promising candidate:
  - Either as reactant in a Fuel Cell System
  - Or as a combustive fuel an engine



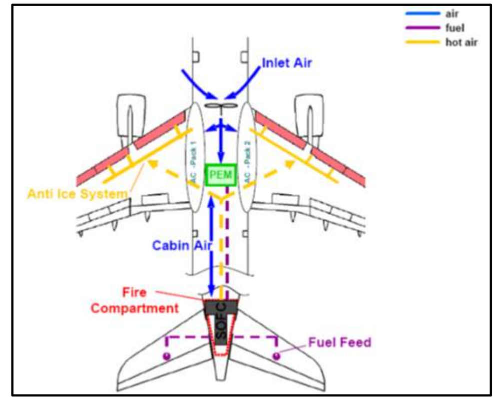


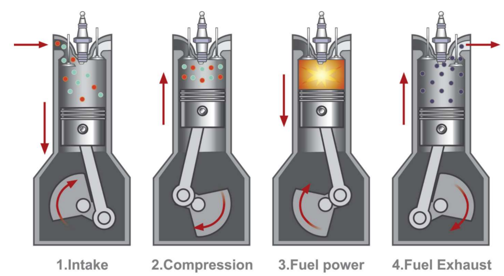
Hydrogen, a new substance on board

- Hydrogen (H2) has specific hazards, with own characteristics.
- Predominant (mostly feared) are fire or explosion.
- Others include:
  - Mechanical/material hazards (i.e. embrittlement, or failure storage systems)
  - Crashworthiness
  - Physiological hazards
  - Cryogenic (for the use of Liquid H2 (LH2))
  - Fueling and handling hazards

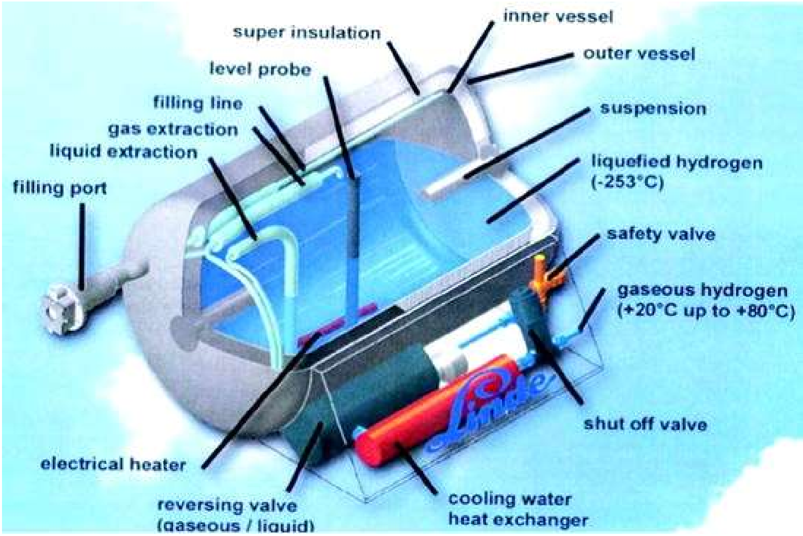
Different possible utilisations of H_2 foreseen

- As reactant in a fuel cell, generating electrical power for, i.e.:
  - Energy for Propulsion
  - Aircraft Galley Power Trolley Cart
  - Emergency Power (e.g. replace main battery, RAT)
  - Stand Alone Power:
    - Medical evacuation
    - Electronic warfare
    - Maritime surveillance
  - Auxiliary Power System
- As combustion fuel in stead of jet fuel.





Storage and distribution



Pure Hydrogen:

→ Liquid

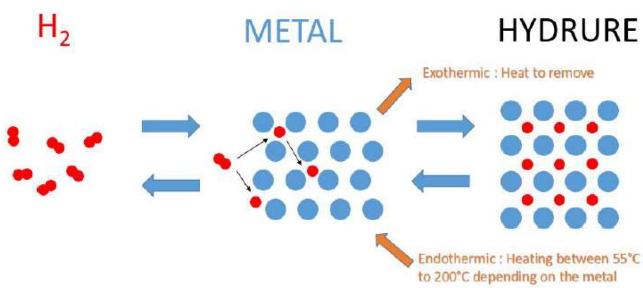
→ Gaseous

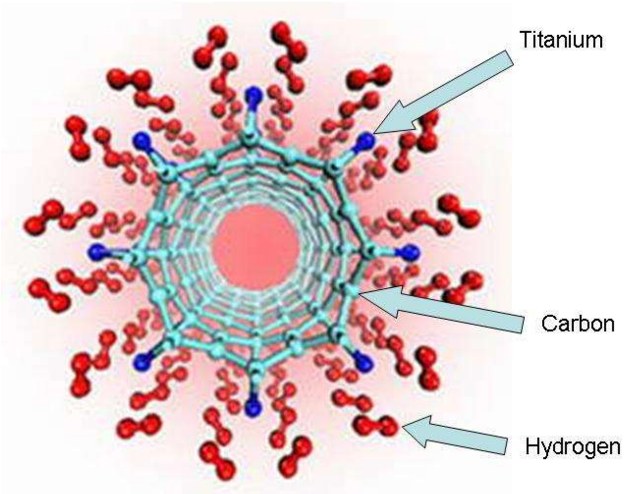
Examples of other storage possibilities:

→ Hydrocarbons (reforming)

→ Solids (Metal Hydrides, on surfaces, etc)

→ Water (electrolyse)





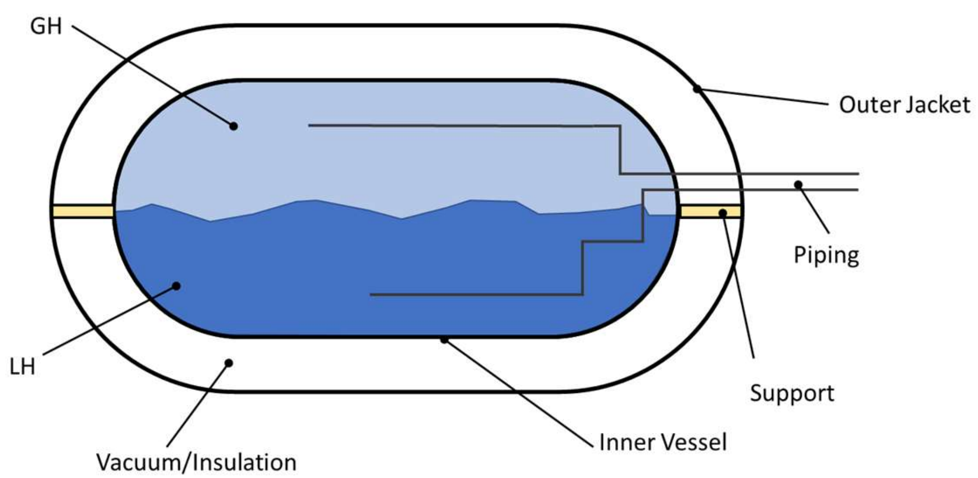
Liquid H2 storage

Liquid storage

→ H_2 is liquid T<20°K (-253°C), cryogenic

→ At ca. 1 bar 5 kg H_2 is stored in 75 litre tank

→ Currently used in space propulsion



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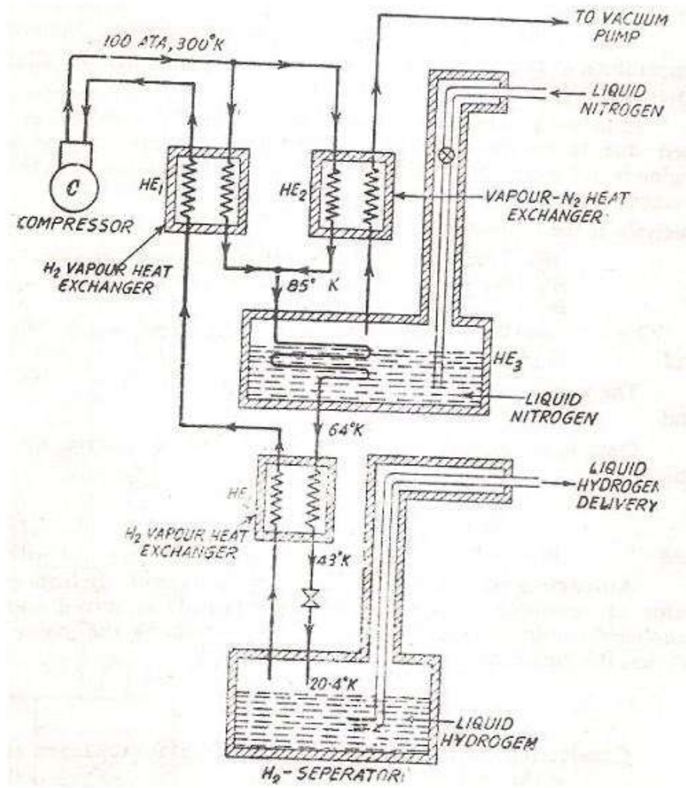
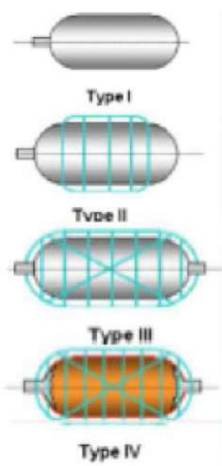
Liquid H2 storage

- → Liquid storage is a mature solution
- → Relatively low pressures (<12 bar)
- → Liquefying H_2 requires:
  - → very pure H_2
  - → ortho to para conversion (@20K 99% para)
- → Expensive both in costs and energy



Gaseous H2 storage

→ Different pressure vessel types, III and IV light weight and high pressure vessel



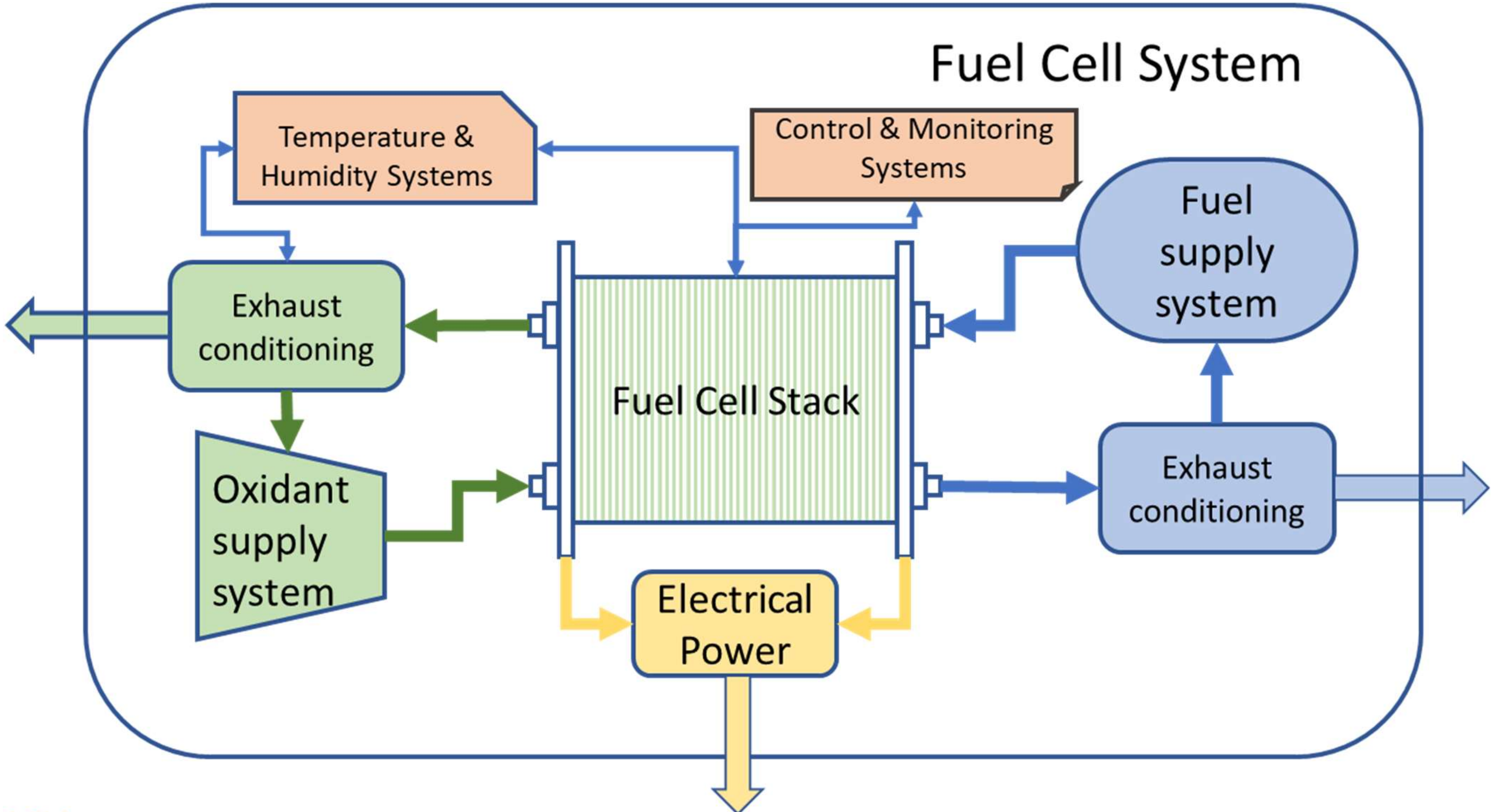
Type I	Pressure vessel made of **metal** (mainly for stationary application (SA))
Type II	Thick **metallic** liner hoop wrapped with **a fiber-resin composite** (SA)
Type III	**Load-sharing** liner fully-wrapped with a **fiber-resin composite** (portable applications (PA))
Type IV	**Non load-sharing** liner fully-wrapped with a **fiber-resin composite**.

Gaseous H2 storage

Compressed gaseous

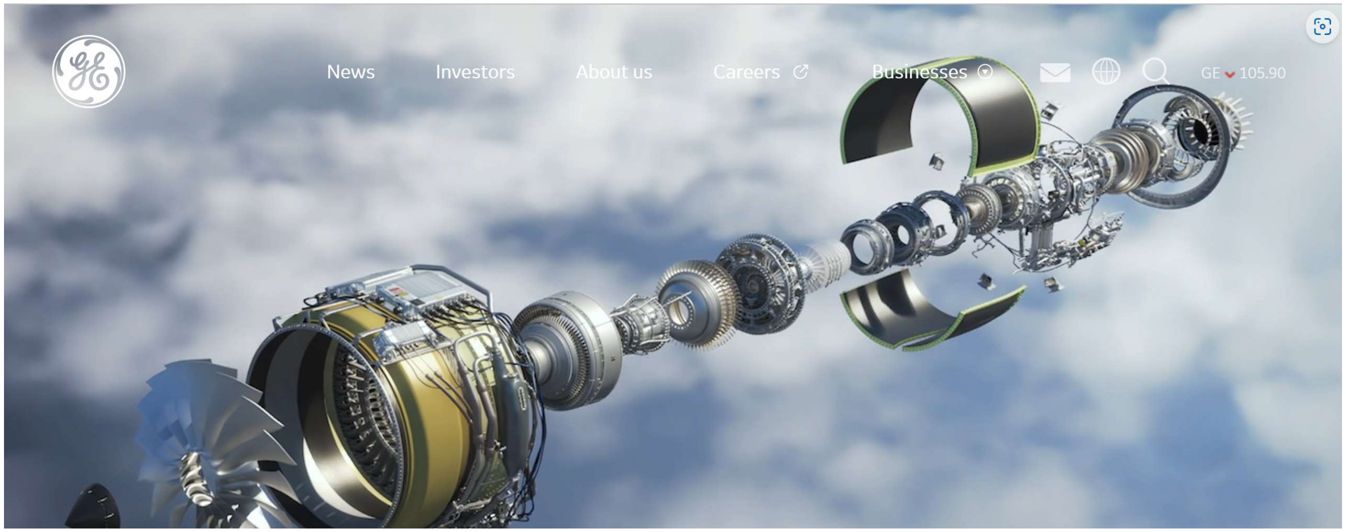
→ At 700 bar, density of H_2 is 42 kg/m^3: 5 kg H_2 fits in 125 litre tank

→ Cars use this technology, giving a range of 600 km


Fuel Cell System
Temperature & Humidity Systems
Control & Monitoring Systems
Fuel supply system
Exhaust conditioning
Fuel Cell Stack
Oxidant supply system
Exhaust conditioning
Electrical Power

H2 Turbofan/Turbopropeller

→ H2 can directly feed turbofan/turbopropeller engine combustion chamber



Fire and explosion risks

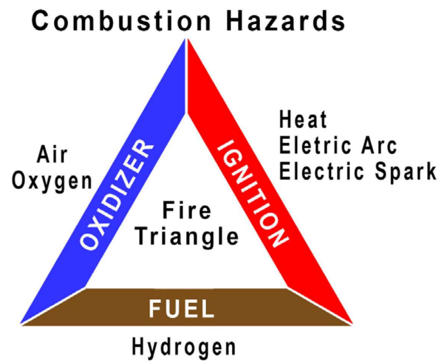
Hydrogen Combustion

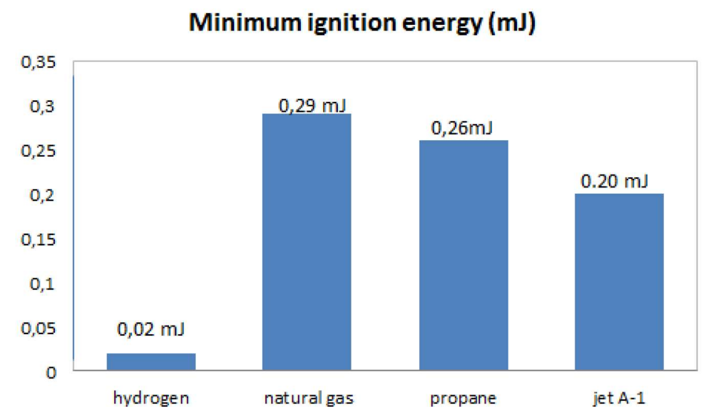
→ 3 elements needed

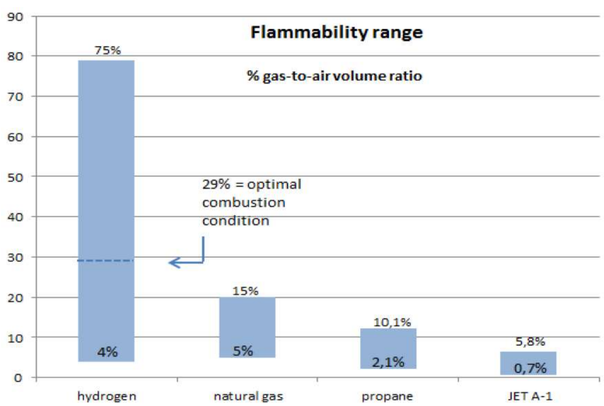
→ Auto-ignition T: 538 °C

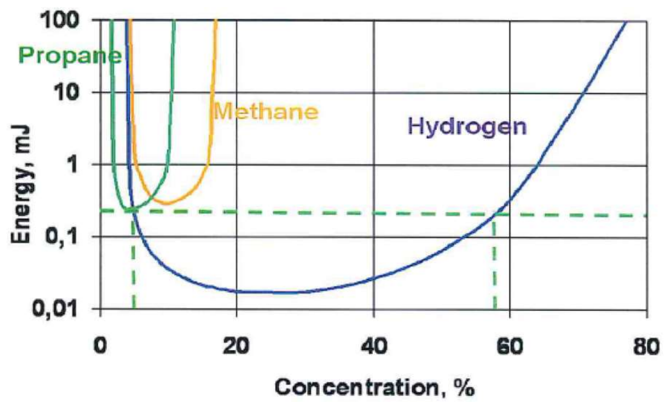
→ Wide flammability range vs concentration

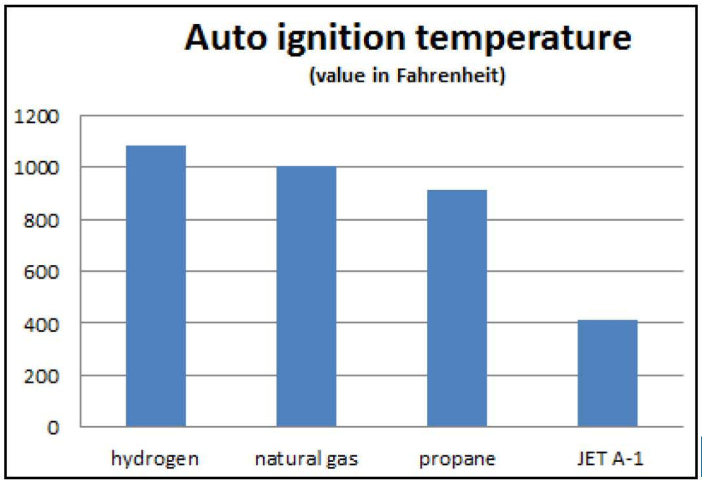
→ Low ignition energy











Fire and explosion risks

- Hydrogen flame is pale blue
- Adiabatic flame T:
  - H_2/Air -> 2045 °C
  - H_2/O_2 -> 3200 °C

- Little infrared heat, but substantial ultraviolet radiation:
  - Even close, only little sensation of heat for a human being

Hazards summary

- H2 fire and explosion hazards:
  - H2 ignition
  - H2 combustion
  - H2 fires: microflames, H2 deflagration, H2 detonation
- Flammable mixture ignition:
  - Due to electrical sources
  - Due to mechanical sources
  - Due to thermal sources
  - Resonance ignition
  - Flammability limits

H2 Fire/Explosion Challenges

Product Safety Objectives

- Example for assessing (CS-25) regulatory impacts:
  - Maintain the same level of safety achieved by circa 70 years of fire/explosion regulatory evolutions for large airplane commercial transport: H2 presence shall not degrade this achieved level.
  - Keep the spirit of CS-25 Fire & Explosion Safety requirements that are:
    - **PRESCRIPTIVE and DESIGN ROBUSTNESS** oriented
    - **NUMEROUS**: in all CS-25 subparts with:
      - **GENERAL rules** (i.e CS 25.1309 CCA with FESRA PRA's, minimization with CS 25.863,…)
      - **SPECIFIC rules** :DFZ adjacent zone with 25.1182, Tank Safety with CS 25.981/954, Designated Fire Zones with CS 25.1181/ 25J1181, Crashworthiness with CS 25.963/25.993/25.994, Occupant protection from external fire with CS 25.856,...
      - **MULTI-LAYERS rules**

        Supplementing : CS 25.981 over CS 25.1309

        Overlapping: Requirement for DFZ, FFLZ, FZ …

A few fire/explosion problematics

- Zone Concept Issue : H2 presence on-board aircraft is impacting existing fire/explosion requirements and already defined fire/explosion risk zoning. Possible new concept to address specificities.
  - Impact onto Designated Fire Zone (DFZ), Flammable fluid Leakage Zone (FFLZ), Fire Zone (FZ), zone adjacent to DFZ (xx.1182), 2D-Nacelle, …
  - Impact on Fuel Tank Safety (FTS) perimeter applicability:
    - H2 distribution is likely to be treated as an H2 tank is to be treated
    - A flammable fluid leak is supposed to be a failure condition not a nominal condition (porosity). Strategy to be defined but likely to be treated under fuel tank safety rather than an FFLZ (leak is a failure).
  - New zone for electrical fire threat : Electrical Fire Withstanding Zone (EFWZ)
  - New zone for fuel cell fire threat : Fuel Cell Fire Withstanding Zone (FCFWZ)

A few fire/explosion problematics

- H2 Fire Extinguishing
  - Issue : Potential loss of one fire layer of protection with no (H2) performant fire extinguishing agent/system
    - Today CS-25 requires 2 shots capability
  - Do not imply that fire extinguishing agent/system will not be necessary
    - Presence of other flammable fluids (oil, hydraulics)
    - Residual burning from H2 fire exposure
  - Is reliance placed on H2 supply shutting off sufficiently balancing the loss of that fire protection layer?

A few fire/explosion problematics

- H2 Fuel Tank Safety
  - Issue : CS 25.981 is a 2 layers, self sustained rule concept
    - The intent of the 2 layers probably need to be redistributed
    - Whereas there was some different treatment between classic fuel distribution and classic fuel storage (ullage presence) : it may no longer be true for H2 distribution/storage
  - Inversed concept:

CS 25.981	Classic Fuel Tank	H2 Tank + Distrib.
Prevention	Ignition source prevention with low probability	Minimize ignition risk
Minimization	Minimized exposure to flammability range	Prevent exposure to flammability range with low probability

A few fire/explosion problematics

- H2 Explosion
  - Fuel Tank Safety: Is a tank explosion “containment” and Continued Safe Flight and Landing (CSFL) path still an option?
  - General : Is it one explosion problematic or 2 problematics with deflagration and detonation to be addressed?
    - Possibly a design robustness intent for deflagration
    - Possibly a minimum design features and a low probability approach for detonation
    - Will have to play on prevention from moving from deflagration to detonation

A few fire/explosion problematics

- H2 Combustor Burnthrough
  - CS-2x makes some assumptions that a flame can exit the turbine engine combustion chamber (CS 2x.903)
    - Parallel with combustor burn through flame (25.903, British Standards Institution Specification 3G100: Part 2: Section 3: Sub-section 3.13, dated December 1973/ AC 20-135)
    - Flame: 3min, 1700°C (3000°F), 350-550 psi, 1-inch diameter.
  - Issue :
    - What sort of H2 flame to deal with?
    - How do we come to a standard?

A few fire/explosion problematics

- H2 Fire in a powerplant environment
  - CS-Definition
  - Assumes:
    - A temperature
    - A heat flux
    - 2 time durations
  - Recognizes:
    - Steel (Titanium) and Aluminum material equivalency to fire exposure duration
  - Issue :
    - Need to understand how those assumptions could be invalidated with H2 and what could be the new one
    - Note: that notion of fire size does not exist, neither distance at which the fire is standardized: does it need to be defined in the context of H2?
    - Note: H2 Fire presence duration is a minimum of 5min (based on crew reaction – same assumption as for classics fuel installation). Plus a certain duration - to be determined - for fire presence after crew reaction/procedure intitiation.

A few fire/explosion problematics

→ H2 Fire in a powerplant environment: getting a standard

→ How was it done for ISO2685/AC 20-135 ?

- Historic - Genesis of ISO2685 / AC 20-135 for Powerplant (jet fuel) Fire Testing

- In summary:
  - Prompted by **in-service issues** with an urgent need for a fire test program. (1939)
    - DC-3 Pratt & Whitney 1830-B (Wasp) from 1939 to 1941.
    - Curtiss Wright CW-20 installation with the engine and Waco YKS-37. Ending around 1943
  - Lot of **full scale testing**
  - **Progress with time**

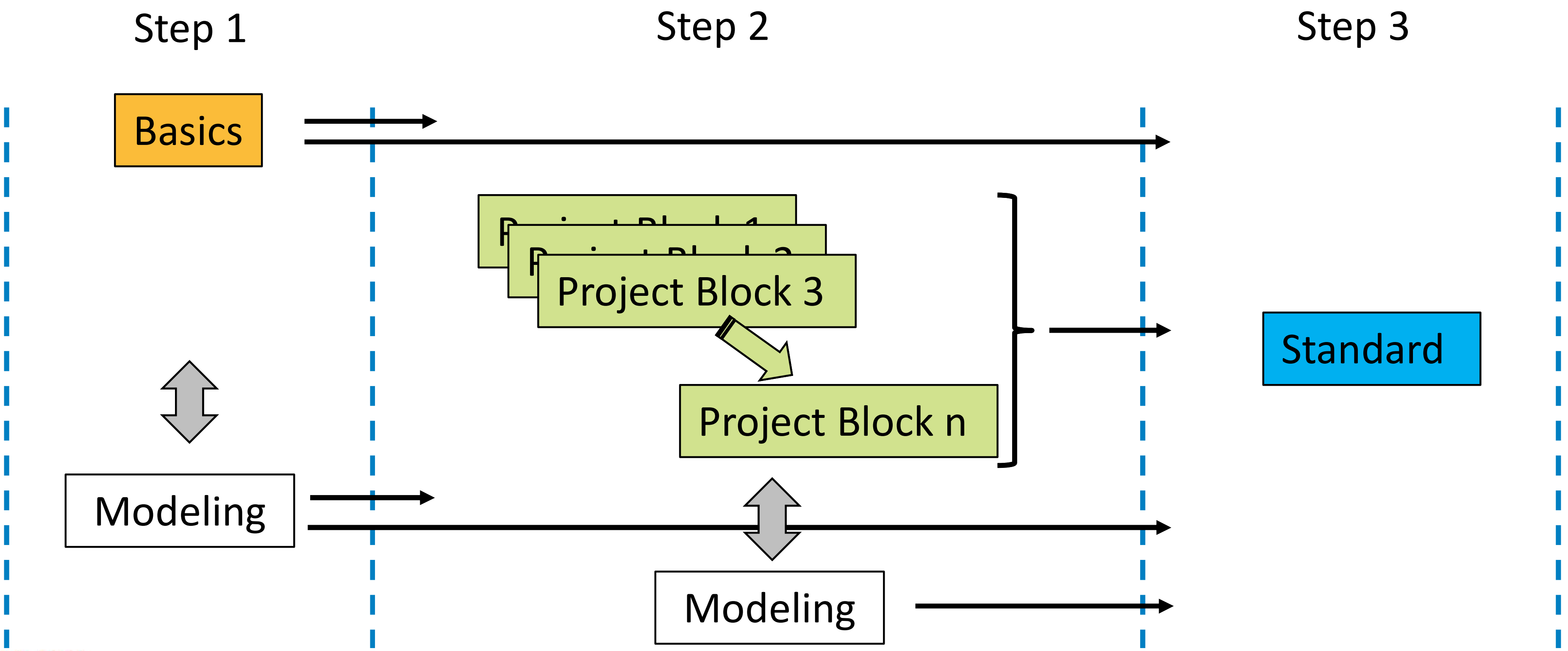
Organization / Time Frame	Development Test Reports	Powerplant Regulations
CAA; 1939 to 1950s	• Engine/nacelle fire tests • TD No. 31 & No. 33, 1943 • Various other test reports	• CARs 4 (aircraft) & 13 (engine), 1946 • SRR No. 259, 1947
FAA; 1960s-1980s	• Power plant Installation fire tests (NA-69-26, 1969) • Oil burner Reevaluation (RD-76-213, 1976) • Various other test reports (Power plant Report 3A, etc…)	• SRR No. 453, 1961 • FAR regulations • AC 20-135 Draft (1988)
FAA; 1990 to current	• Next Gen burner test reports (various) • Propane vs kerosene comparison test reports (various)	• 14 CFR regulations • AC 20-135 (1990) • AC 33.17-1 (2002); 33.17-1A (2009) • AC 20-135 Change 1 (2018)

A few fire/explosion problematics

- → H2 Fire in a powerplant environment: getting a standard
- → How to do it?
  - ➢ Will not wait **in-service issues**
  - ➢ **Full scale testing** is part of the process
  - ➢ **Progress with time**
- → Could be a progression from basics understanding and characterization supplemented with data from project blocks and dedicated standard testing activities, all with support of modelling.

A few fire/explosion problematics

→ H2 Fire in a powerplant environment: getting a standard



A few fire/explosion problematics

- BASICS

H2 flame

Litterature Review

Testing - BASICS
Flame
- Free
H2 Flow
- Explore
Measure
- Temperature
- Heat Flux
- Size vs f(flow)
  - T mapping (x,y,z)
  - HF mapping (x,y,z)
Repeatibility

H2 flame duration

Litterature Review

Assumptions - Analysis - BASICS
f(trapped volume, leak rate)

H2 material withstanding capability

Litterature Review

Testing - BASICS
Coupons testing
- Sheets
- Tubes
Different Material - Aviation
- Steel
- Titanium
- Aluminum
- Composite, Elastomeric
Thickness
- Standard (vs known FR/FP)
- Explore (till 5min / 15min)
Measure
- Melting duration
- Burnthrough duration
- Skin temperature
Repeatability

Flame-to-specimen distance

Testing - BASICS
Distance
- Standard (vs known fire testing conditions)
- Explore
Repeatability

A few fire/explosion problematics

- PROJECT BLOCK

H2 Leak	H2 flame	H2 flame duration	H2 material withstanding capability

H2 Leak

Failure Combination Assumptions

FMEA (design dependent)

Leak Characterization
- Defect database
- From FMEA
- Simulated defects
- Defect variation

Measure
- Leak rate: f(defect, flow conditions)

H2 flame

Full Scale Testing (design dependent)

Flame
- Free
- **Closed**

H2 Flow
- **From Leak Characterization**

Measure
- Temperature
- Heat Flux
- Size vs f(flow)
    - T mapping (x,y,z)
    - HF mapping (x,y,z)

H2 flame duration

Full Scale Testing (design dependent).
- f(trapped volume, leak rate) **from design and leak characterization**.

Measure
- **Flame duration**
- **T = f(t)**
- **Hazardous quantity**

H2 material withstanding capability

Full Scale Testing (design dependent)

TC design

Measure
- Melting duration
- Burnthrough duration
- Skin temperature

Flame-to-specimen distance

Full Scale Testing (design dependent

Distance
- **From design**

A few fire/explosion problematics

- STANDARD

Scaling Down

Specimen Definition

Apparatus Standardization

Operating Instructions

Material Recognition

Test Duration

Repeatability

Determine Max & Average with deviations (temp.)

Determine Max & Average with deviations (heat flux)

Determine Min, Max & Average with deviations (specimen to leak distance)

Review Events and Reliability / Maturity
- Events
- Reliability & Tracking Plan

Determine Min, Max & Average with deviations (leak flow)

Testing Supplement as necessary (representative population)
- Free Closed Flame Testing
- Full Scale Testing

Leak Characterization

Project Block 3

Project Block 2

Project Block 1

Basic

Modelling

A few fire/explosion problematics

In-flight fires: zonal analysis

- H2 leak in pressurized areas:
  - increased risk of explosions
  - even concentrations of hydrogen below the lower flammability limit could adversely affect the flammability performance of materials and constructions
  - higher level of severity of the fire threats in critical zones: inaccessible areas, cargo compartments, but also in occupied areas
- Mitigating measures:
  - Prevent leakage from hydrogen systems to other non-powerplant zones
  - Ventilation / detection / isolation

A few fire/explosion problematics

Post Crash fire

→ When using Hydrogen as fuel, the fire hazard resulting from a Hydrogen leak after a crash may be very different compared to that resulting from traditional types of fuel, due to the Hydrogen phenomenology:
  → LH2 “instantaneous” evaporation upon leaking
  → LH2 interaction with Air
  → Gaseous H2 lighter than air
  → H2 ignition can lead to Jet flame or explosion (deflagration / detonation)
  → H2 Bleve risk (inside the tank)
  → H2 flame is barely visible

A few fire/explosion problematics

Post Crash fire

→ Need to reconsider flammability standards:

- → Burnthrough protection achieved through CS 25.856(b) may be inadequate: new performance based requirements need to be specified
- → Meeting current certification specifications (e.g. for Large Aeroplanes CS 25.853 and CS-25 App. F Parts II, IV and V) may not be sufficient to maintain survivable conditions in the cabin until safe evacuation is achieved.
- → Minimum performance standards for flammability of materials used in the construction of escape slides (ref. ETSO-C69c and Chapter 9 of Aircraft Materials Fire Test Handbook) may not be adequate to withstand a hydrogen fire.

A few fire/explosion problematics

Post Crash fire

→ CS 25.803(a):

Each crew and passenger area must have emergency means to allow rapid evacuation in crash landings, with the landing gear extended as well as with the landing gear retracted, considering the possibility of the aeroplane being on fire.

EASA

A few fire/explosion problematics

Post Crash fire

- → Before launching the emergency evacuation, the crew should have a means to detect the presence of a fire that may affect evacuation from the aircraft: it should be possible to identify a hydrogen fire in any light condition.

- → The location and the level of performance of the available emergency exits, as well as the design and performance of the associated egress assist means, should ensure that evacuees are not directed towards areas inside the cabin or on the ground with risk of lethal injury due to H2 hazard.

A few fire/explosion problematics

Post Crash fire

It may be necessary to replace existing CS-25 requirements and/or, whenever appropriate, to introduce special conditions.

→ CS 25.807(e):

Emergency exits must be distributed as uniformly as practical, taking into account passenger seat distribution.

→ CS 25.807(f)(3):

If more than one floor-level exit per side is prescribed, and the aeroplane does not have a combination cargo and passenger configuration, at least one floor-level exit must be located on each side near each end of the cabin.

A few fire/explosion problematics

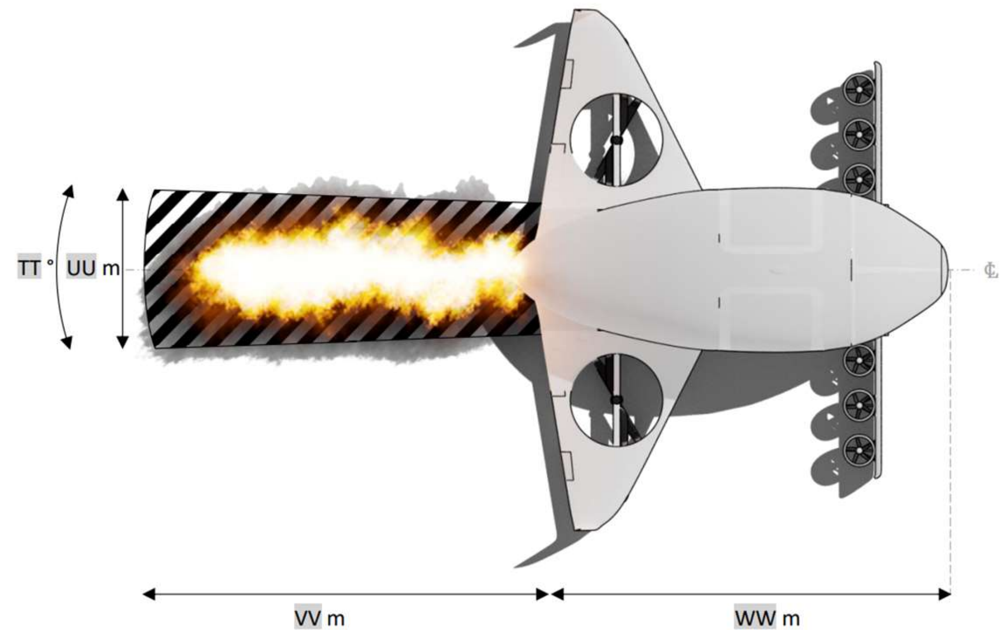
Post Crash fire

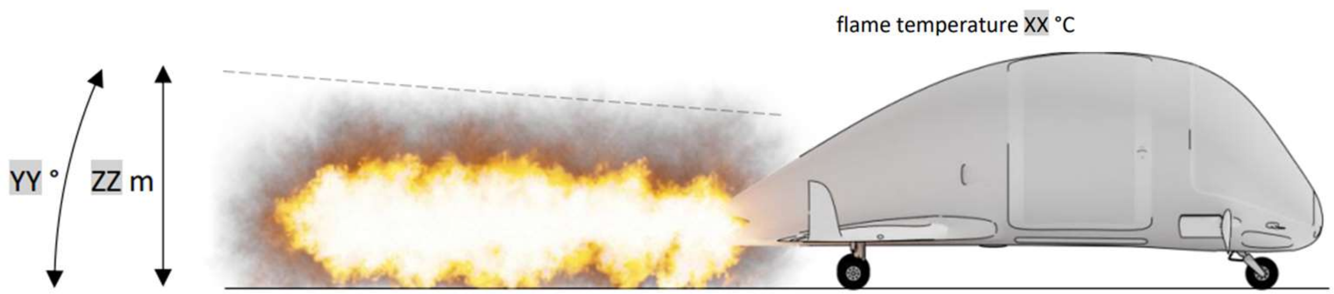
- → Depending on the design of the aircraft, it may be preferrable to concentrate exits in areas that minimize exposure to any hazards generated by the hydrogen systems installation.
- → Evacuees should be directed to safe areas after reaching the ground, at sufficient distance from the aircraft to mitigate the risk of exposure to explosions.

A few fire/explosion problematics

Definition of **Hazard areas** following a similar approach as already proposed by EASA for VTOL aircraft (ref. MOC-2 SC-VTOL Issue 3):

***Hazard areas**: Areas around the aircraft where a hazard to persons or equipment may exist, for example due to moving surfaces, engine exhaust or battery venting in case of fire, should be identified and depicted in the AFM. Corresponding hazard markings should be present on the aircraft.*





A few fire/explosion problematics

- Certainly not exhaustive list of problematics …
  - Batteries fire/explosion risk…

- Looking forward to the discussion:
  - Any missing problematics,
  - priority,
  - working groups initiation…

Thank you!

Please share proposals/concerns:

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