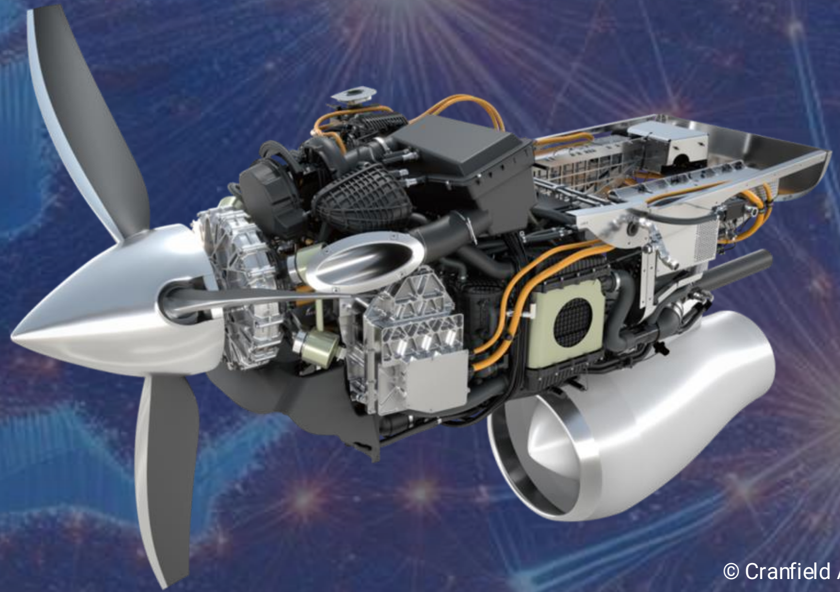
Hydrogen - Powered Aircraft Fuel System



Saai Preetha Dev Varshan
AVD Thermal Systems Engineer

© Cranfield Aerospace Solutions 2025

AGENDA

01 History of H_2 in Aviation

02 Fuel Cell Propulsion System

03 H_2 Fuel System

04 Hydrogen Leakage & Ventilation

05 Purging

06 Emergency Operation

07 Conclusion

08 Q & A

Cranfield Aerospace Solutions

Cranfield Aerospace Solutions

History of H_2

© Cranfield Aerospace Solutions 2025

History of H_2 in Aviation: A Timeline

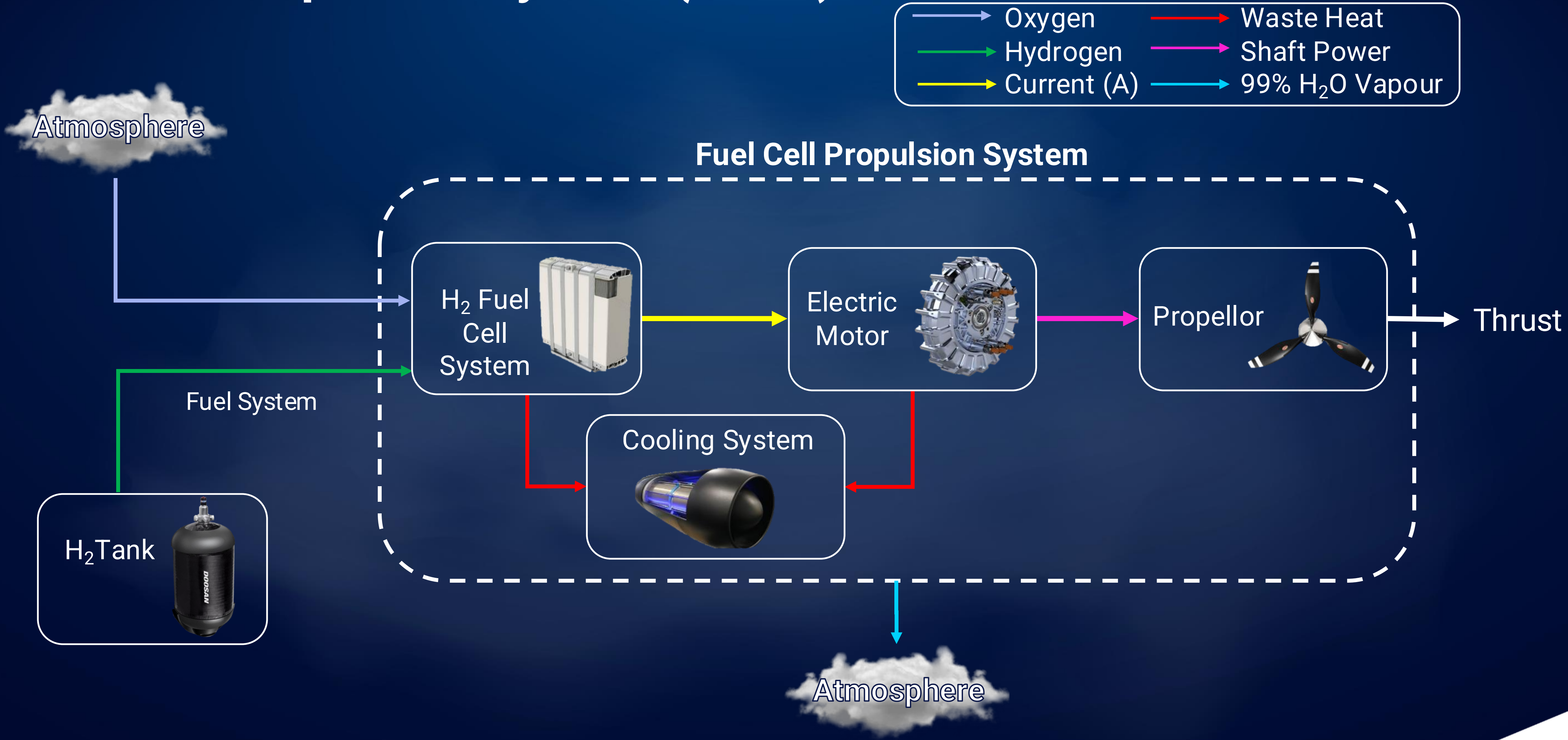
Early Pioneers		Experimental Phase	Renewed Focus	Present

H_2 Buoyant		Burning H_2 - Combustion		H_2 - Fuel cell
Marking the beginning of H_2	Loss of confidence in H_2	Studies begin on Hydrogen-fuelled aircraft	Adapt technology to multiple platforms to drive sales volumes	Clean sheet aircraft design, optimised for zero emissions
1700s to 1800s	1900s to 1930s	1950s to 1970s	1980s to 2000s	2010s to Present

Fuel Cell Propulsion System

© Cranfield Aerospace Solutions 2025

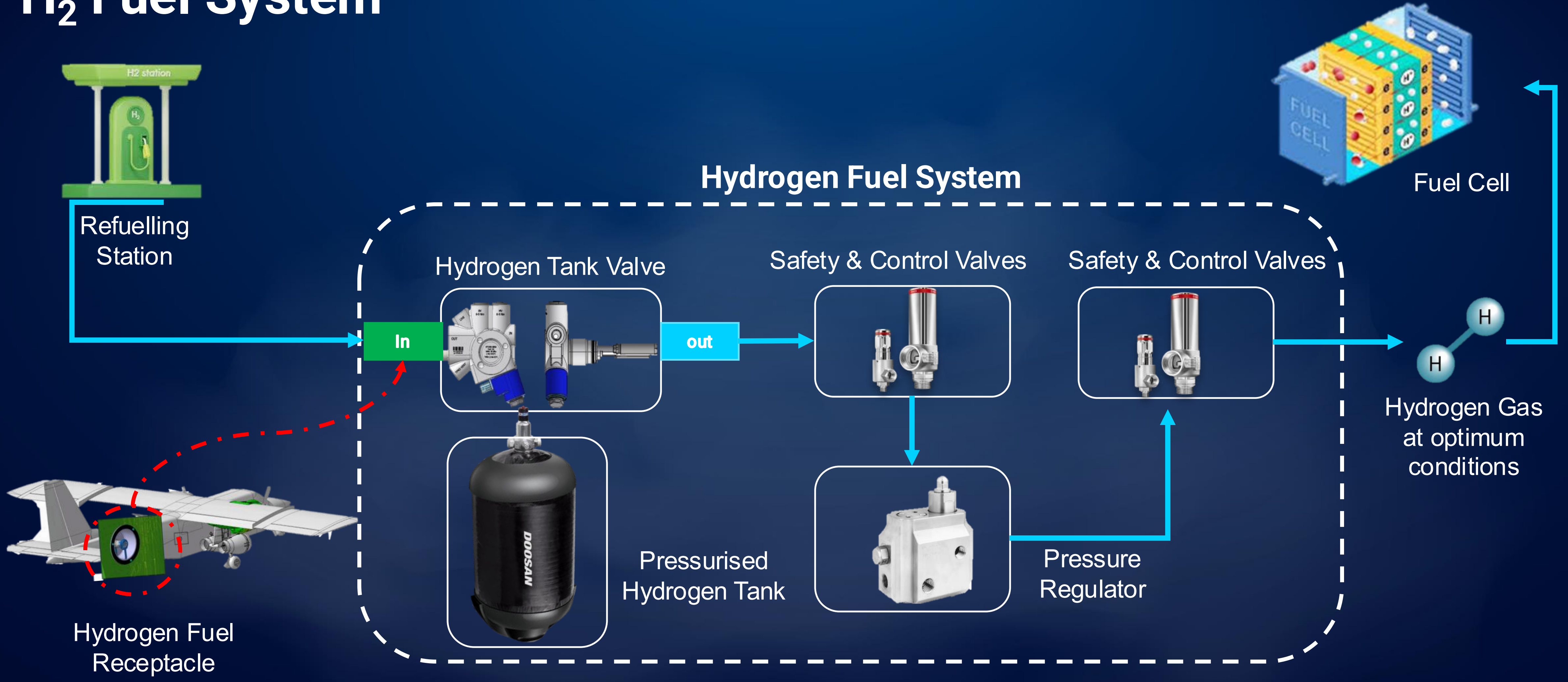
Fuel Cell Propulsion System (FCPS)



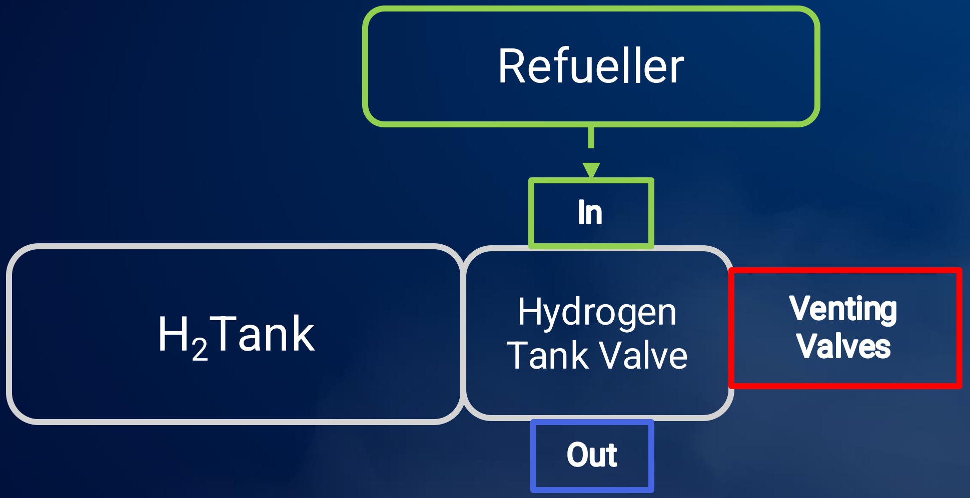
H_2 Fuel System

© Cranfield Aerospace Solutions 2025

H_2 Fuel System

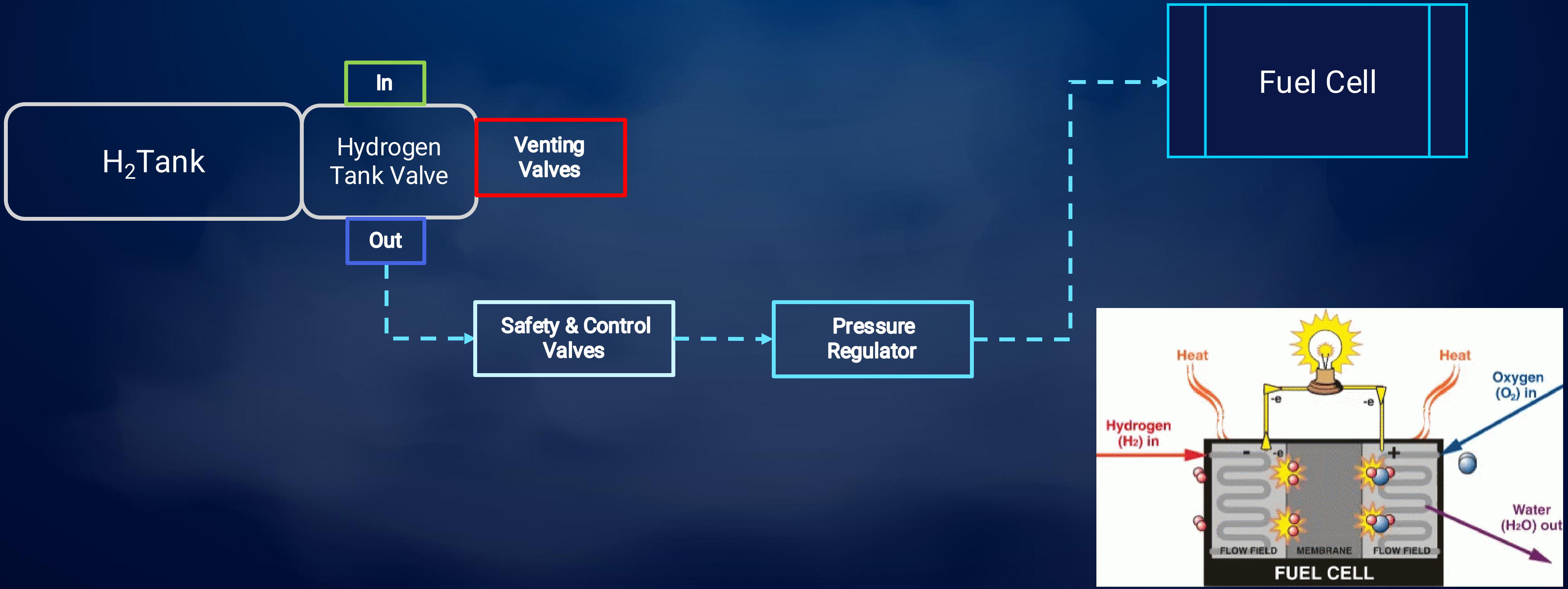


H_2 Fuel System – Fueling



Project Acorn 2024

H_2 Fuel System – Flow of H_2 to Fuel Cell



H_2 Fuel System – Emergency Venting

H_2 Tank

Hydrogen Tank Valve

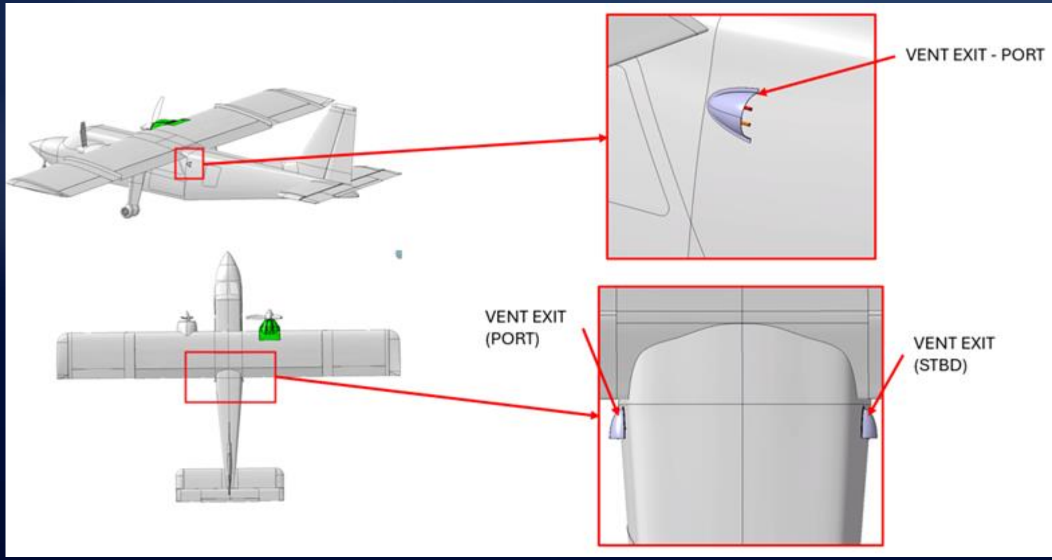
In

Out

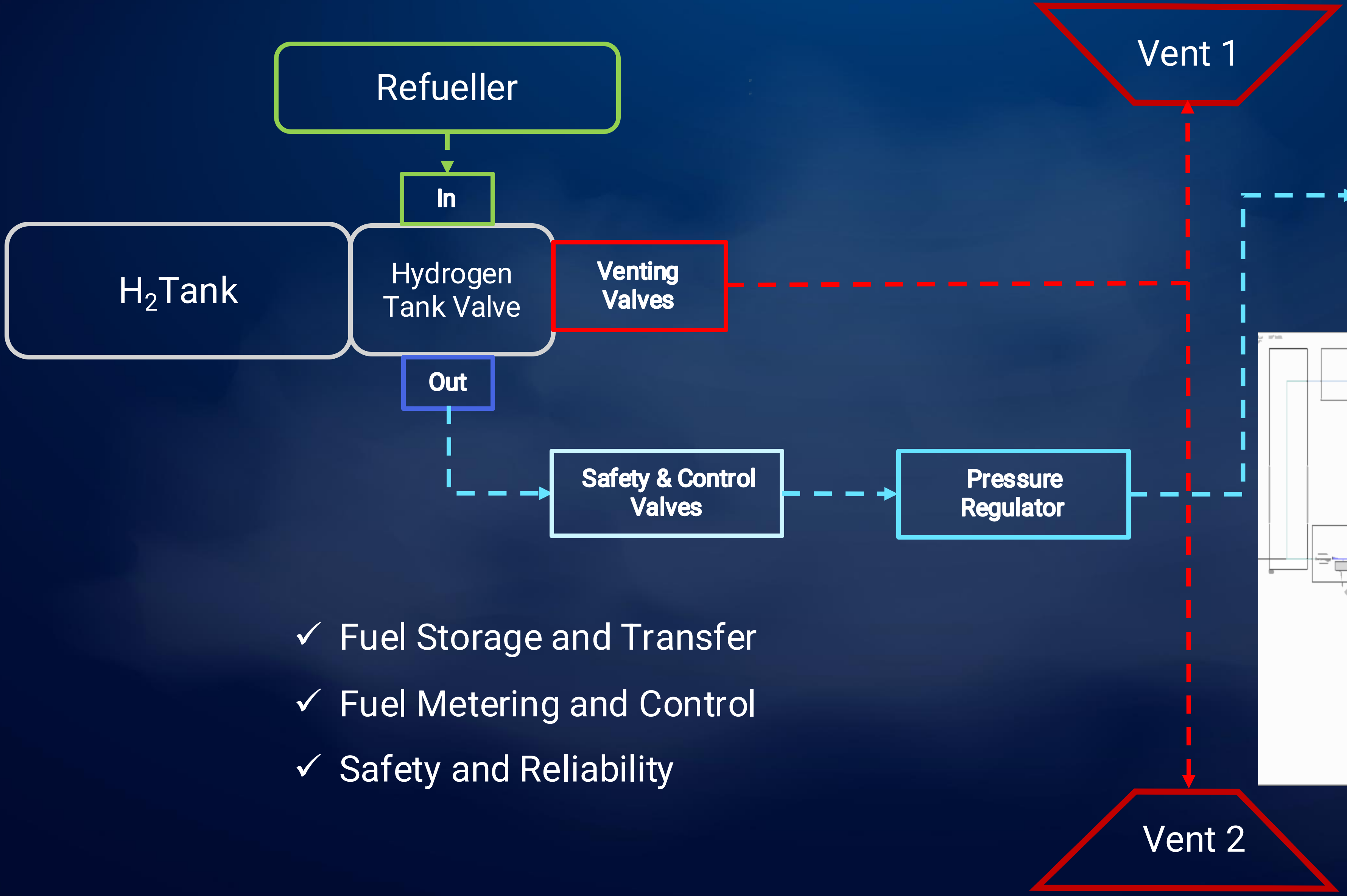
Venting Valves

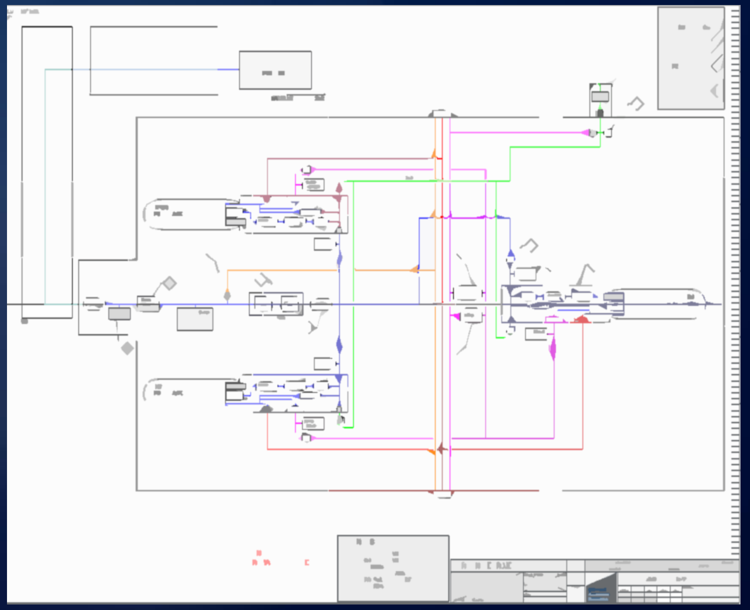
Vent 1

Vent 2



H_2 Fuel System – Overall Schematic





- ✓ Fuel Storage and Transfer
- ✓ Fuel Metering and Control
- ✓ Safety and Reliability

H_2 Leakage & Ventilation

Cranfield Aerospace Solutions

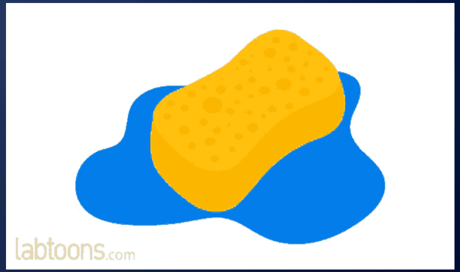
© Cranfield Aerospace Solutions 2025

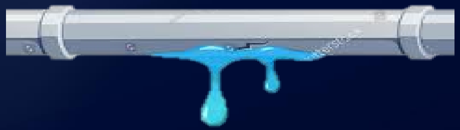
RISE Hydrogen Jet Fire Tests (SH$_2$IFT Project)

Permeation and Leakage

Feature	Hydrogen Leakage	Hydrogen Permeation
Definition	H_2 escaping through unintended holes, cracks, or faulty seals in equipment.	H_2 passing through the solid material of the containment system itself.
Pathway	Physical openings or defects.	Materials
Rate	Sudden and potentially large	Slower and gradual process
Cause	Faults in manufacturing, assembly, or damage to the system.	Inherent property of the material and influenced by factors like temperature and pressure.

Courtesy: LaVision





Ventilation of H_2

1. Identification of H_2 Zones

↓

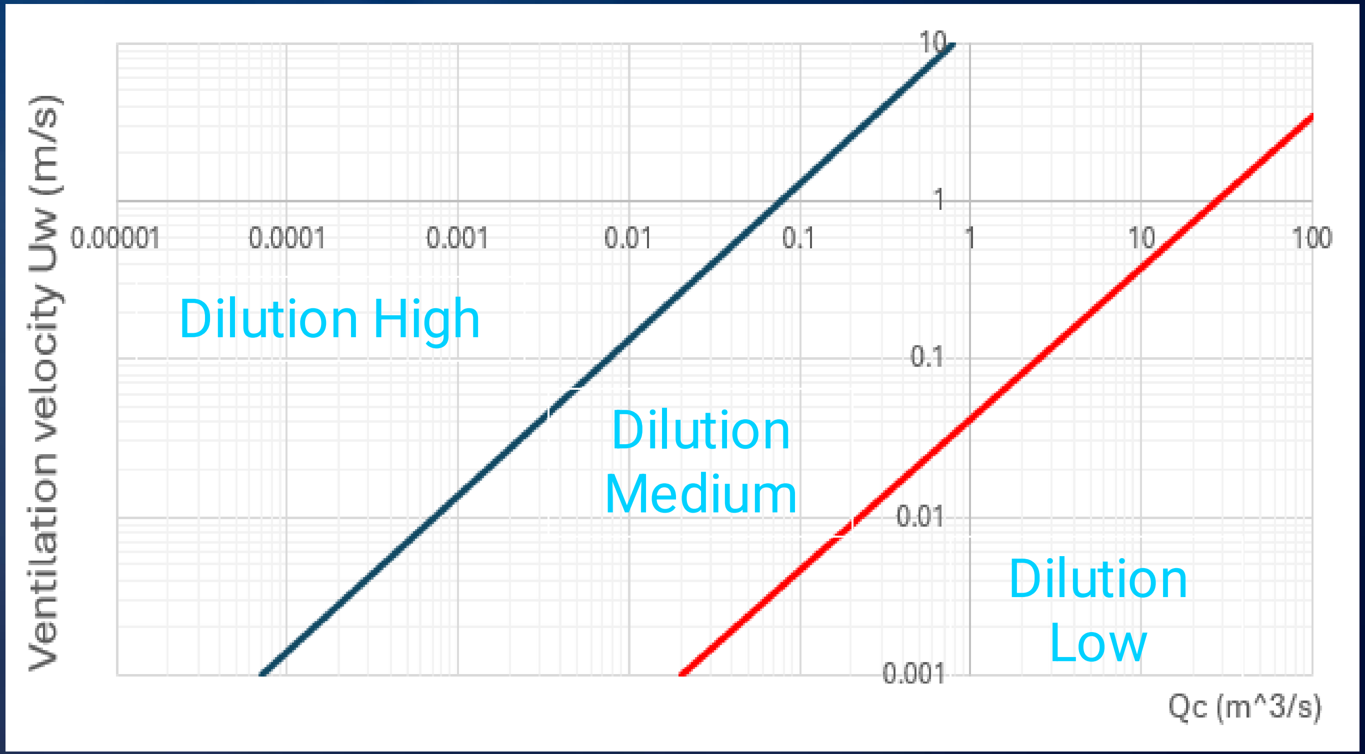
2. Calculation of H2 leakage and permeation rates for each zone

↓

3. Calculation of Ventilation of each Zone

↓

4. Calculation of Dilution of H_2 for each Zone

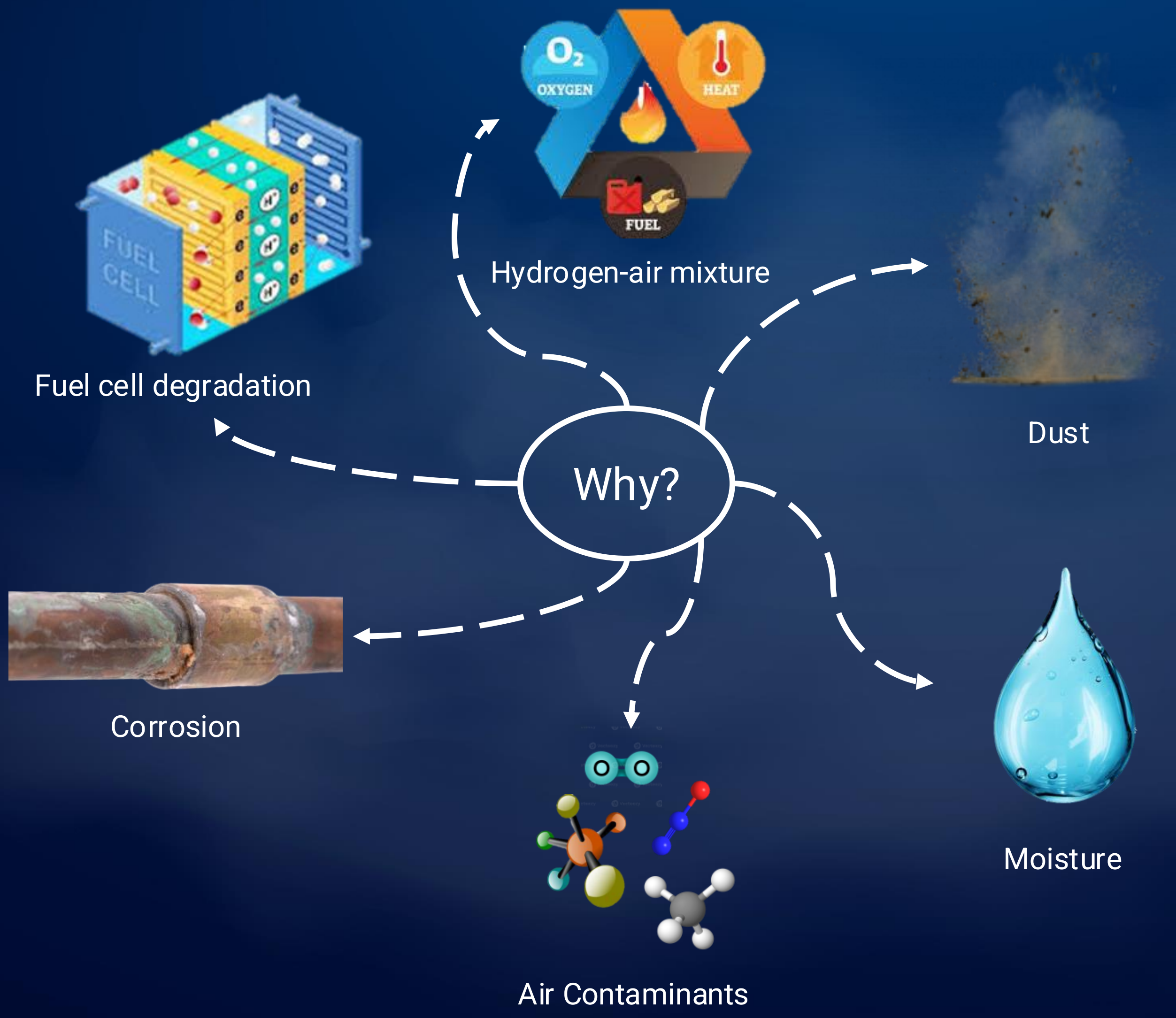


IEC 60079-10 Dilution Chart

Purging

© Cranfield Aerospace Solutions 2025

Purging



When ?

1. Tank Commissioning – N_2
2. Priming – H_2
3. End of operations – N_2

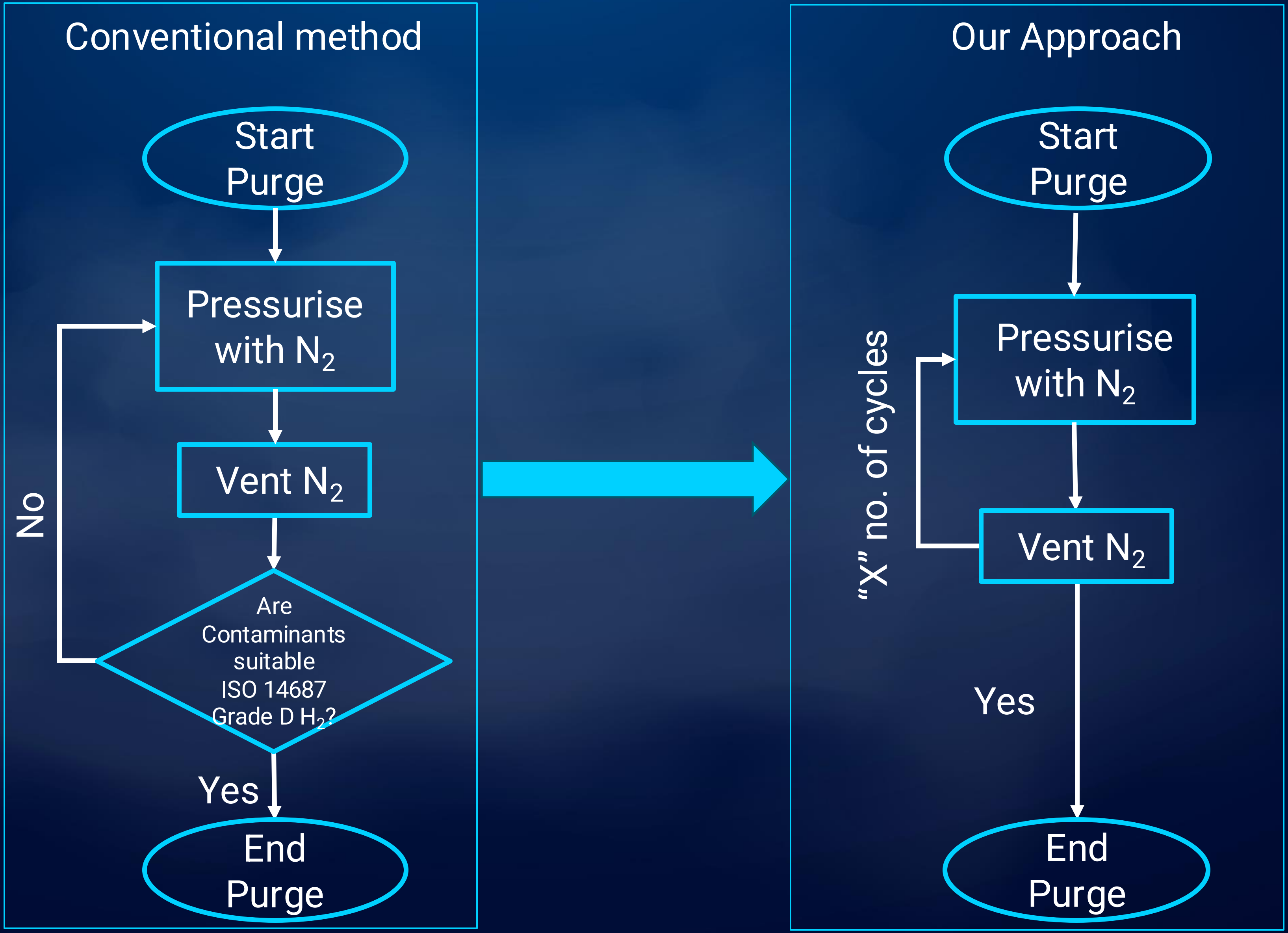
Types

1. Pressure – Venting Cycle ✓
2. Flowing Gas Purge
3. Vacuum Purging

Purging – Commissioning

TYPE I – ISO 14687 Grade D

Impurity	Amount fraction (µmol/mol)
Helium	300
Nitrogen	100
Argon	100
Water	5
Oxygen	5
Carbon dioxide	2
Total hydrocarbon	2
Formic acid	0.2
Carbon monoxide	0.2
Ammonia	0.1



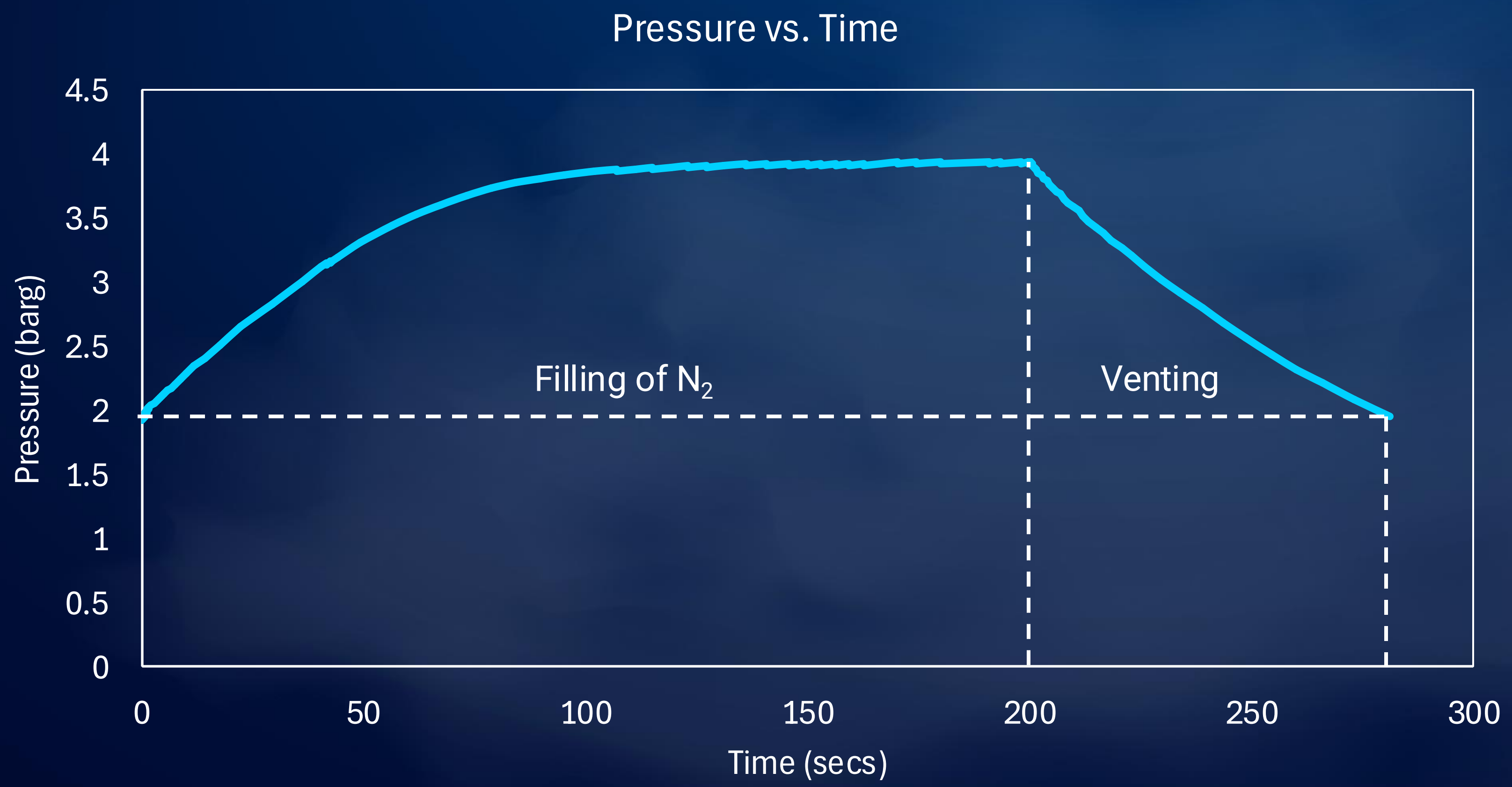
Purging – Calculation

	O_2 Conc.	Tank Pressure	Amount of N_2 used	No. of Cycle
Initial	21%	0 barg	1.93 Kg	1
Intermediate	-	4 barg		
Final	8.4%	2 barg		
Initial	8.4%	2 barg	19.3 Kg	6
Intermediate	-	4 barg		
Final	0.034%	2 barg		

O_2 Impurity = 2.399 μ mol/mol < ISO 14687 Grade D
Purging Calculator

Hydrocarbon processing, How to calculate purge gas volume, D.F. Schneider, Stone & Webster Engineering, Houston, 1993.

Purging – Time Required



- Single Cycle Time ~ 281 secs
- Total Filling Time ~ 23 mins
- Total Venting Time ~ 14 mins
- Total Purging Time ~ 37 mins

Emergency Operation

© Cranfield Aerospace Solutions 2025

Emergency Operation

H_2Tank

Hydrogen Tank Valve

In

Out

Venting Valves

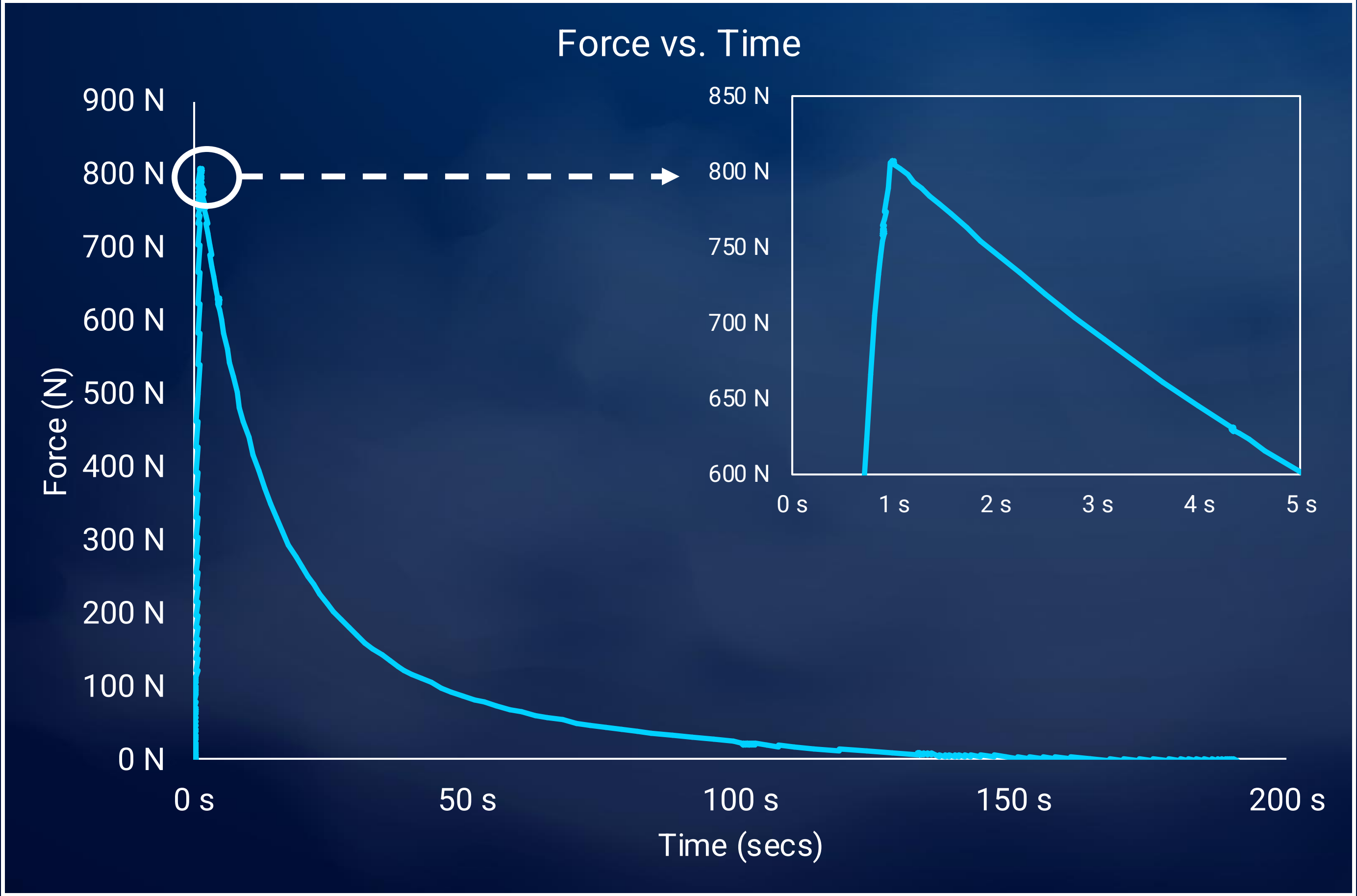
Vent 1

Vent 2

- ✓ Over Pressure Protection
- ✓ Fire Safety
- ✓ Temperature Sensitivity
- ✓ System Integrity

TPRD – Thermally Activated Pressure Relief Device

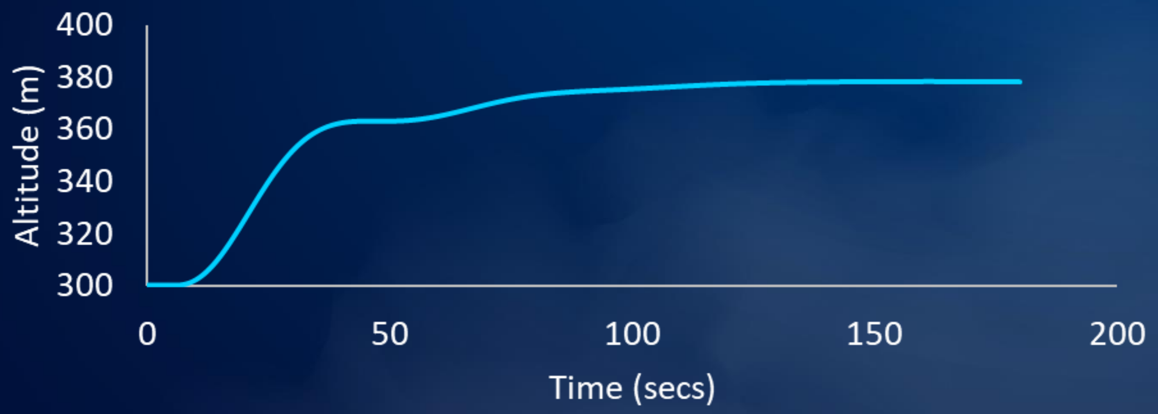
Emergency Operation: Force Generated by a Single Vent



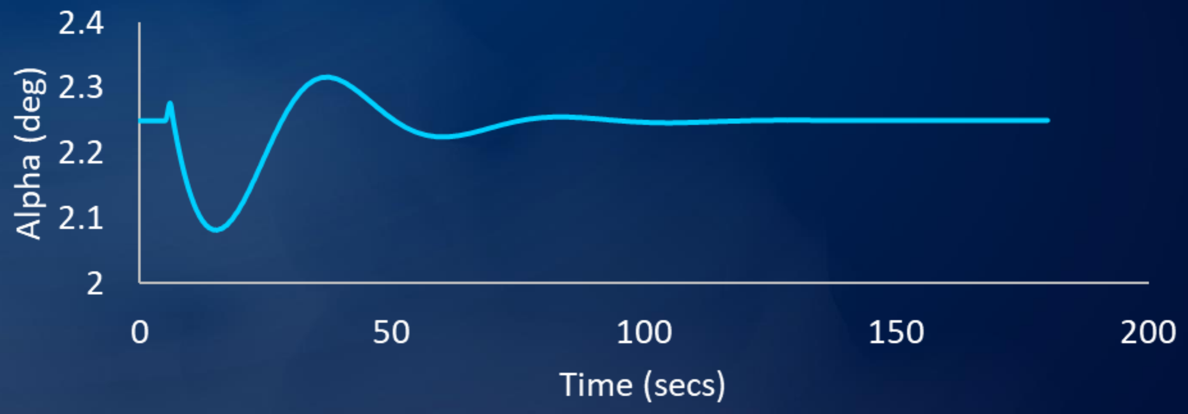
- Combined force ~ 1600 N (two pods)
- Acceleration – 0.05 G
- Vent force ↓ H_2 Pressure ↓
- Hand Calculated values around 800 N per side ~10 secs
- Key parameters – Speed of sound of H_2, Mass flow and Fuel consumption.

Emergency Operation at 130KCAS

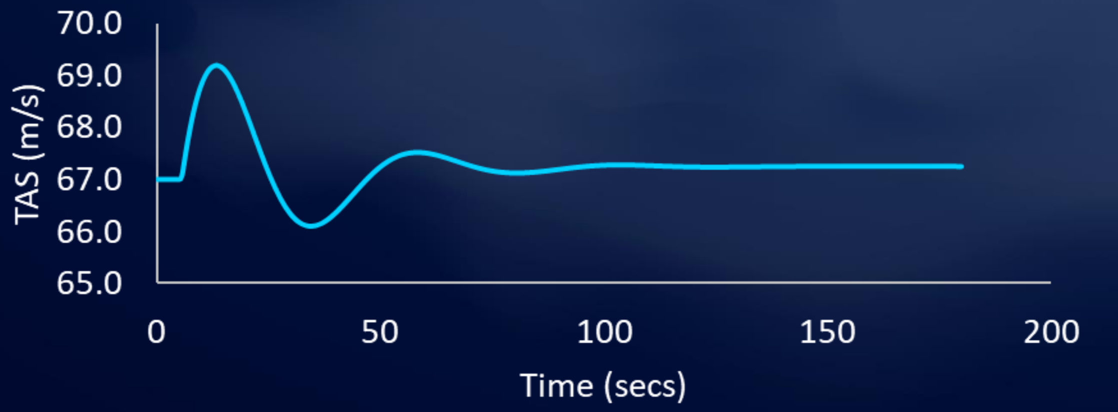
①



②



③



- Aircraft remains in trim & climbed 69m in 40s
- Internal energy ↑ & Aircraft gains Altitude
- Complete event can last up to ~ 2 – 3 mins

Conclusion

1. Mandatory Operations – Purging, Inerting, Venting, Ventilation
2. Emergency Operation – Not Dangerous

Next Steps

✓ Testing

✓ Research and Development

- Hydrogen safety standards
- Aircraft Design and Integration

Quiz Time!!

© Cranfield Aerospace Solutions 2025

What caused the Hindenburg accident?

a) A lightning strike directly hitting the airship.

✓ b) A static electricity discharge igniting leaking hydrogen gas.

c) Sabotage by a passenger or crew member.

d) A catastrophic engine failure leading to a spark.

Source: Nationaal Archief/Spaarnestad Photo

Hydrogen Safety is Key to convincing the aviation regulators and the general public

© Cranfield Aerospace Solutions 2025

What primary safety procedure is initiated if a hydrogen leak occurs during ground operations?

Cranfield Aerospace Solutions

✓ a) Adequate ventilation in the highest point of the hangar

b) Increase the pressure in the tank to stop the leak.

c) Perform a purging cycle using an inert gas like Nitrogen.

d) Drain all the hydrogen from the system into the atmosphere.

© Cranfield Aerospace Solutions 2025

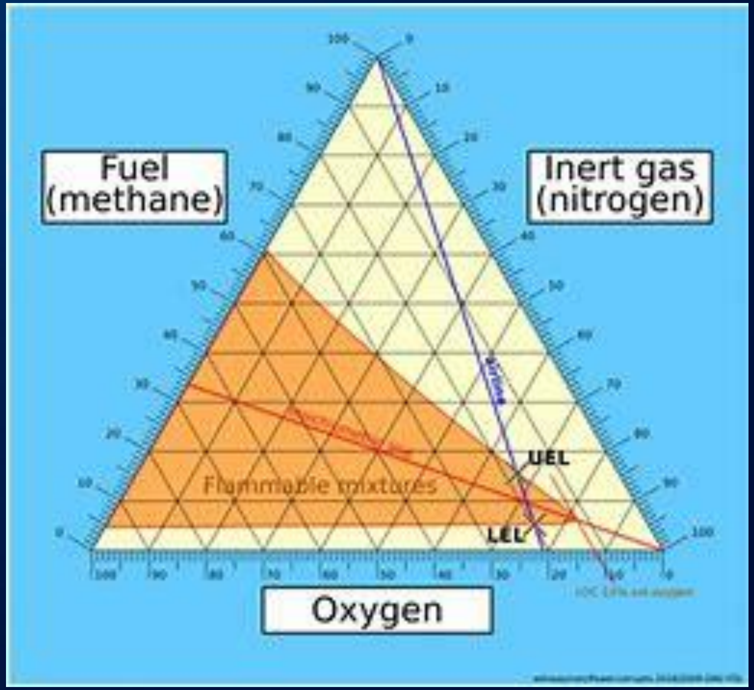
What specific safety hazard is directly prevented by effectively purging the hydrogen fuel system?

a) Over-pressurization of the hydrogen tank.

✓ b) The formation of explosive hydrogen - oxygen mixtures.

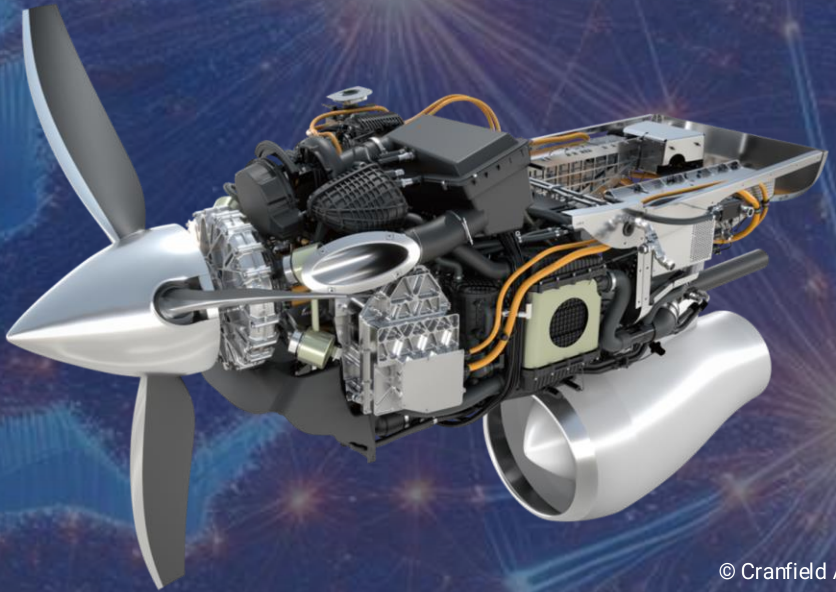
c) Excessive cooling of the fuel cell.

d) External fire near the aircraft.



© Cranfield Aerospace Solutions 2025

Any Questions ?



Saai Preetha Dev Varshan
AVD Thermal Systems Engineer
s.devvarshan@cranfieldaerospace.com

© Cranfield Aerospace Solutions 2025

Backup Slides

Cranfield Aerospace Solutions

Purging – Reducing O_2 Concentration

Initial Filling Of N_2

O_2 Concentration

O_2 Concentration	Pressure	
21%	2 barg	Initial Tank Pressure
↓	↓	
8.4%	4 barg	Intermediate Tank Pressure

Amount of N_2 used = 1.93Kg
No. Cycle = 1

Venting Of N_2

O_2 Concentration

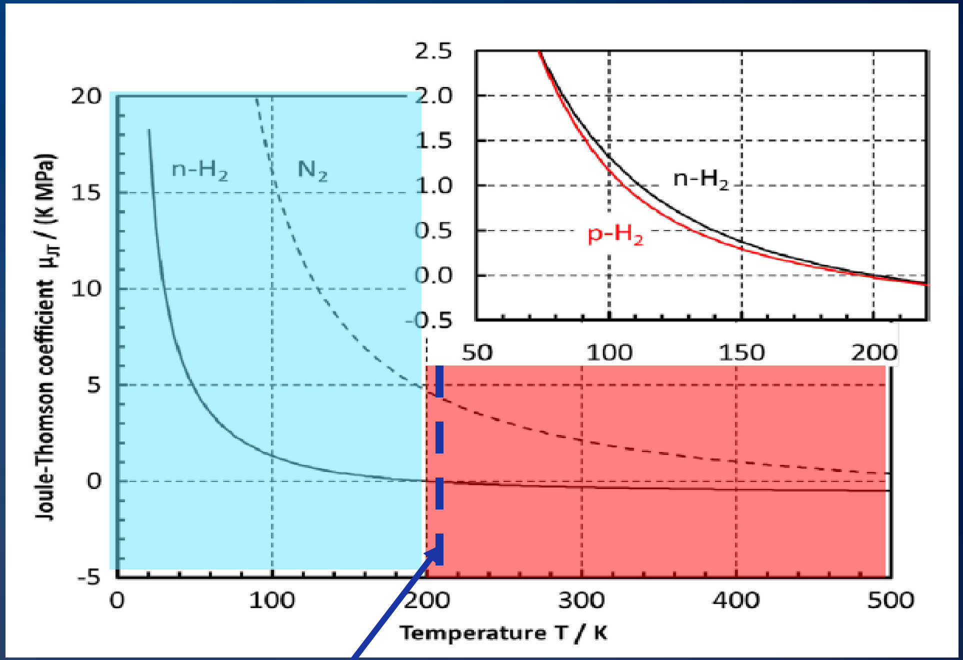
O_2 Concentration	Pressure	
8.4%	4 barg	Intermediate Tank Pressure
↓	↓	
0.002%	2 barg	Final Tank Pressure

Amount of N_2 used = 28.97 Kg
No. Cycle = 9

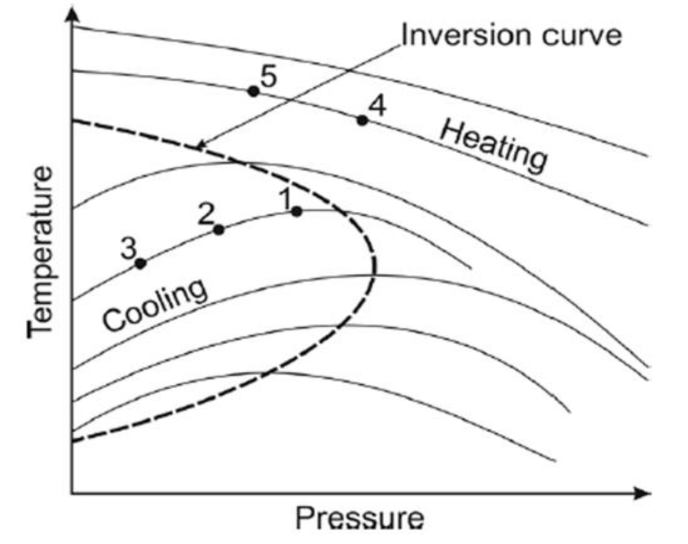
Hydrocarbon processing, How to calculate purge gas volume, D.F. Schneider, Stone & Webster Engineering., Houston, 1993.

Physical properties of H_2

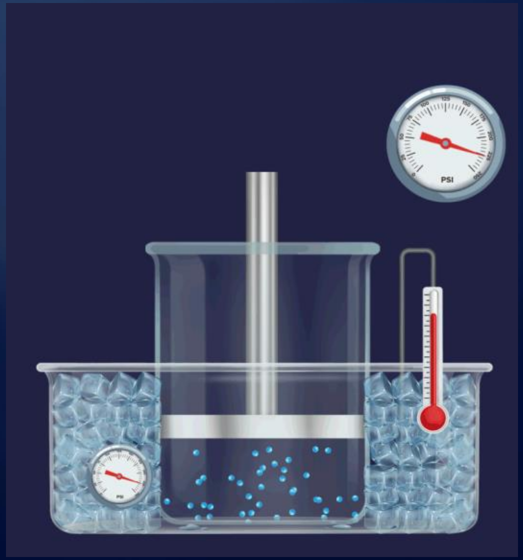
- The gas temperature decreases or increase upon expansion
- Auto-ignition temperature of Hydrogen
  - 858 K at 1 atm and 620K at low pressures
- Wide flammable range: 4% – 75%



202 K
Inversion
Temperature



- Invisible flame
- No smell
- Very low MIE
- High diffusivity
- Highly buoyant



Cranfield **Aerospace Solutions**

Purging – Reducing O_2 Concentration

Initial Filling Of N_2

O_2 Concentration

21%	2 barg	Initial Tank Pressure
↓	↓	
8.4%	4 barg	Intermediate Tank Pressure

Amount of N_2 used = 1.93Kg
No. Cycle = 1

Venting Of N_2

O_2 Concentration

8.4%	4 barg	Intermediate Tank Pressure
↓	↓	
0.0344%	2 barg	Final Tank Pressure

Amount of N_2 used = 19.37 Kg
No. Cycle = 6

Hydrocarbon processing, How to calculate purge gas volume, D.F. Schneider, Stone & Webster Engineering., Houston, 1993.

Purging – Why does concentration matter ?

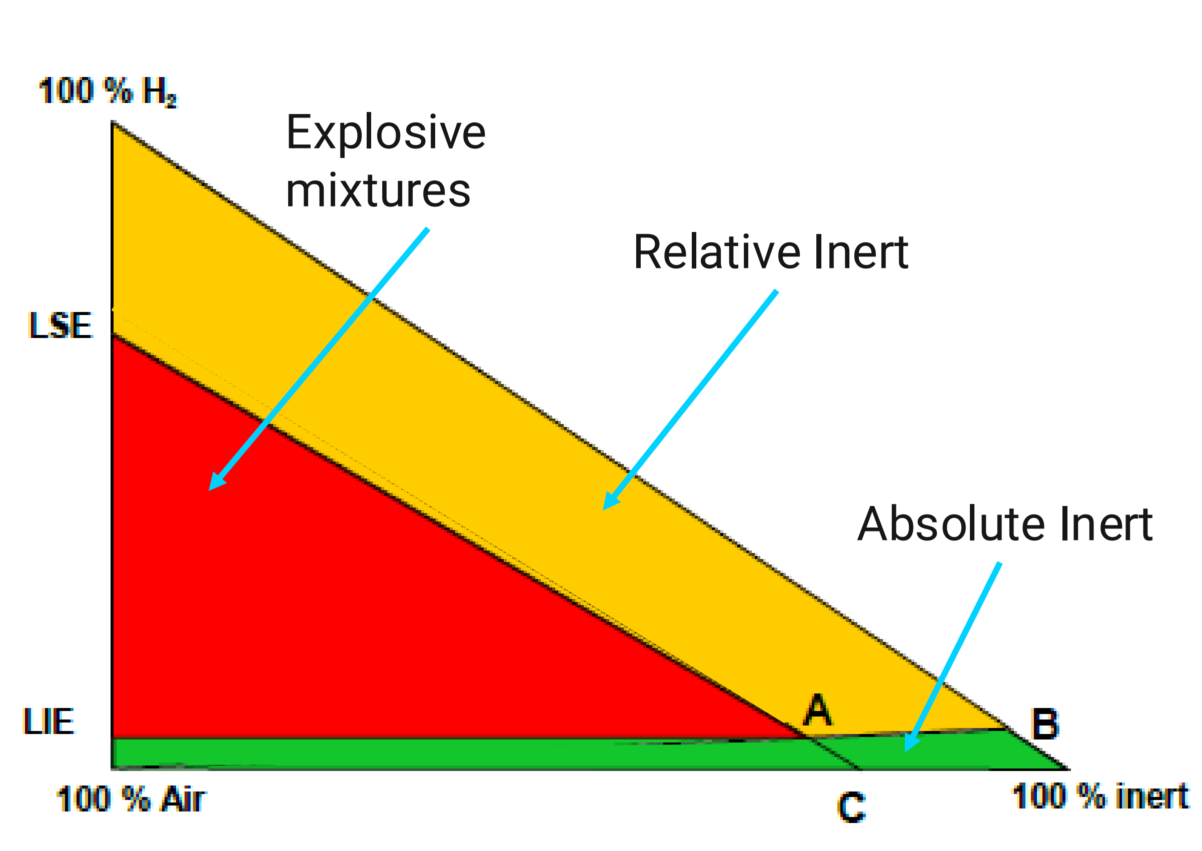


Fig: Triangular Diagram for ternary Hydrogen – Air – Inert mixtures

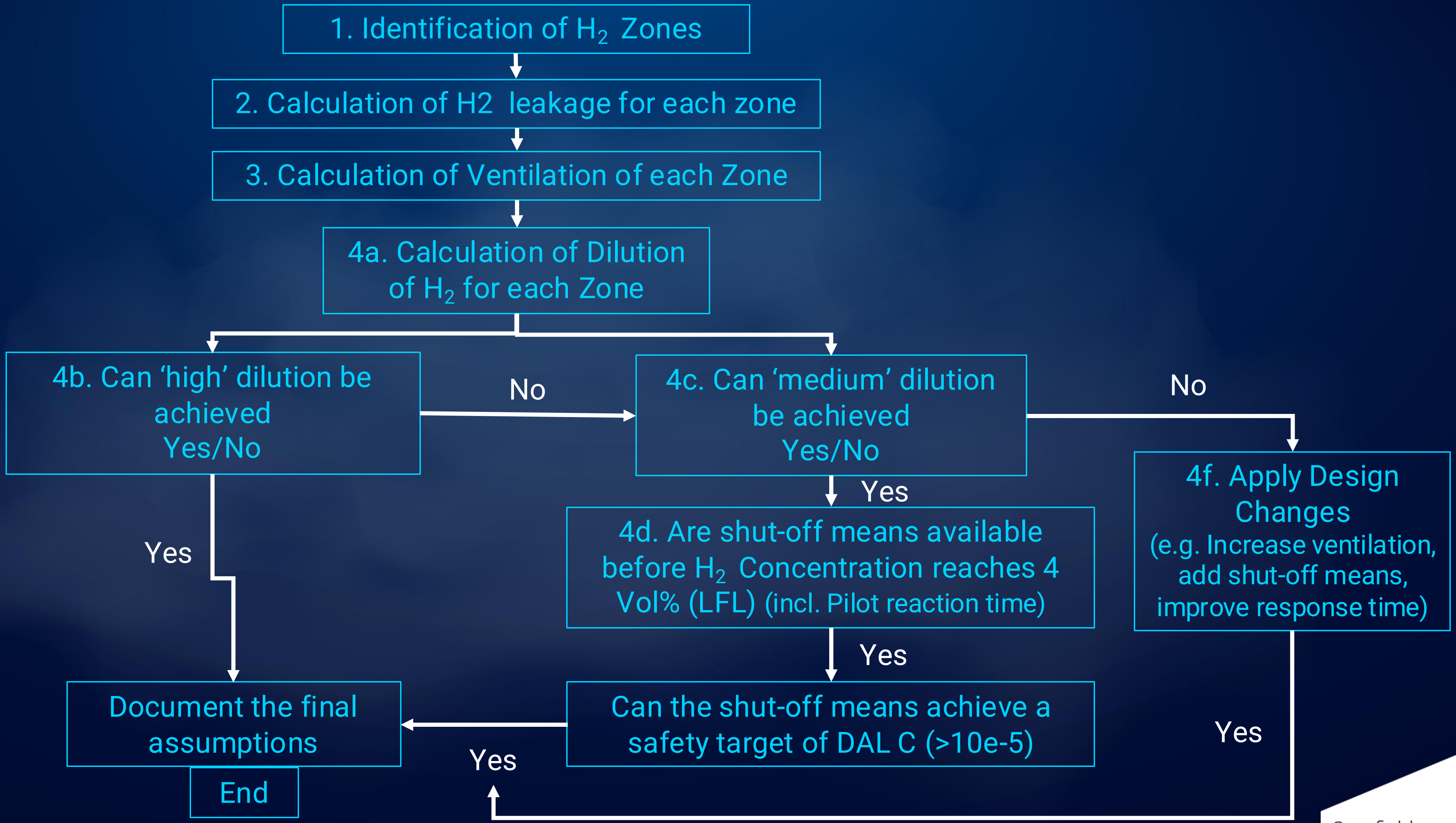
- LEL (Lower Explosion Limit): 4% vol.
- UEL (Upper Explosion Limit): 75% vol.

- LAC (Limiting Air Concentration)
- LOC (Limiting Oxygen Concentration)

LOC = 0,209 LAC

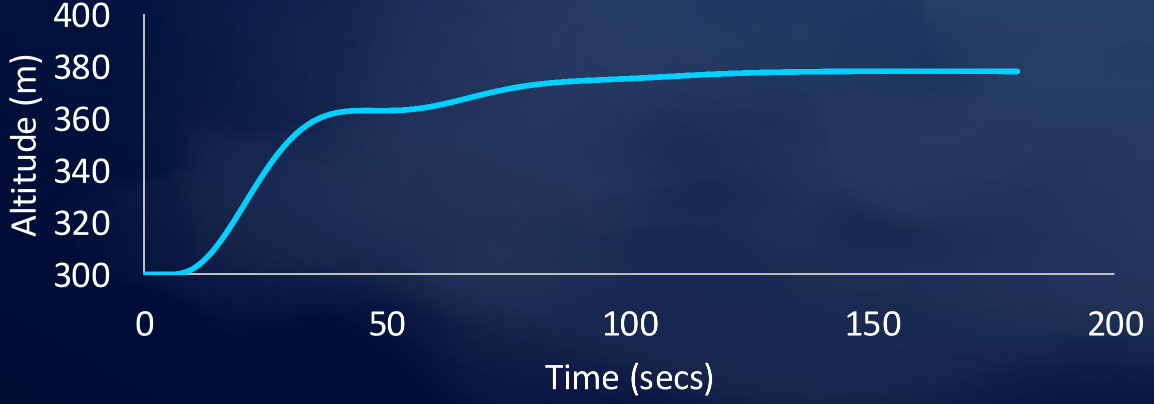
Biennal Report on Hydrogen Safety, “Chapter:5 Hydrogen Safety Barriers and Safety Measures,” Version 1.0 - May 2006.

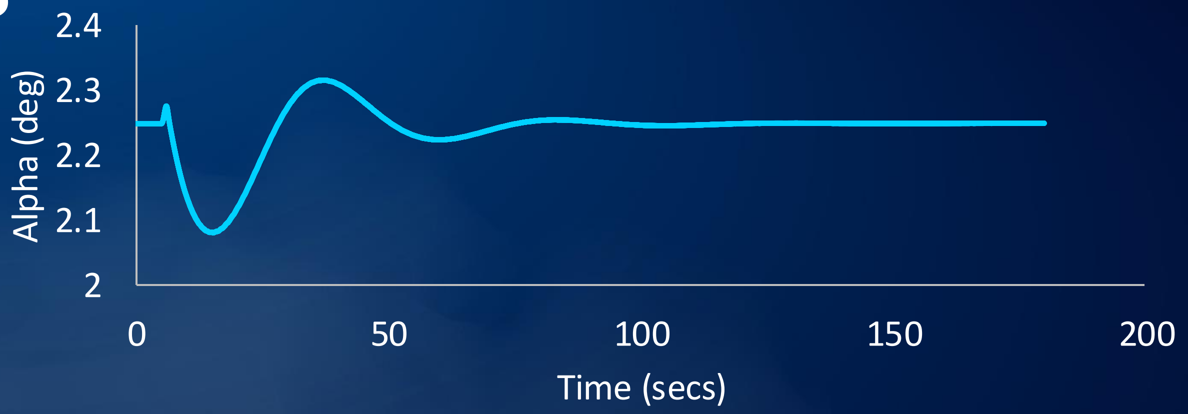
Ventilation

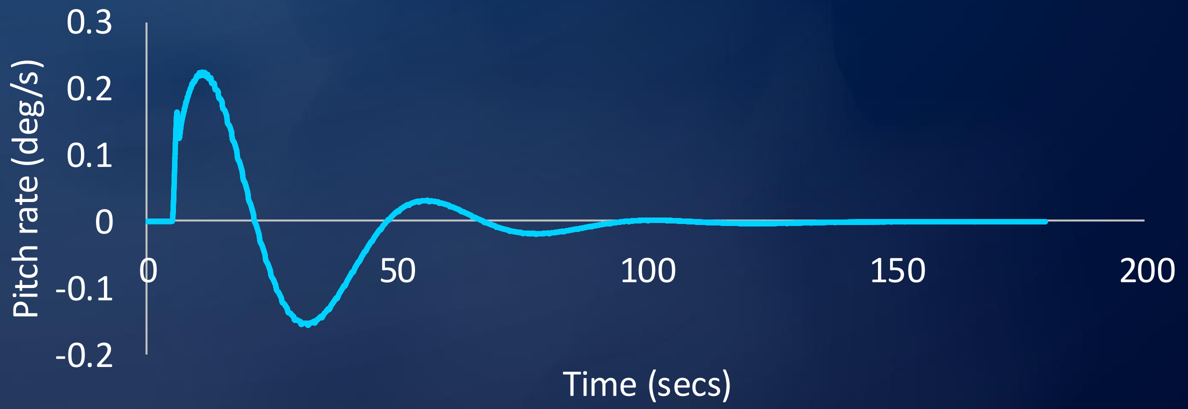


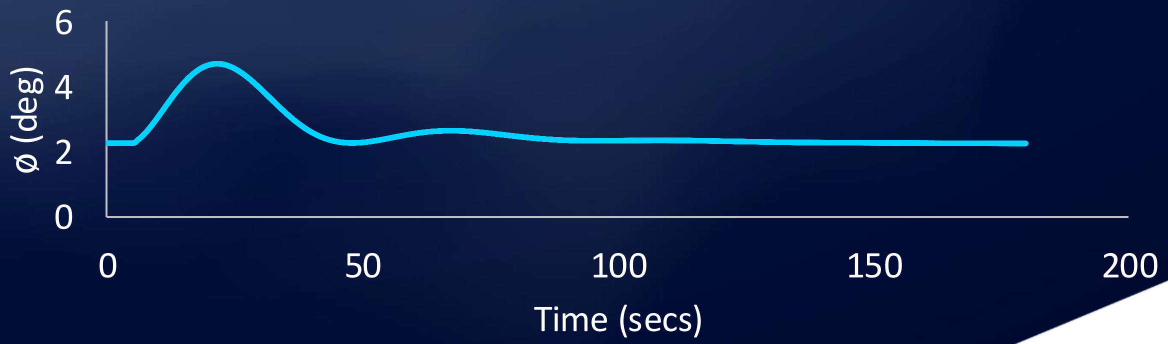
Cranfield **Aerospace Solutions**

Emergency Operation at 130KCAS









Cranfield **Aerospace Solutions**

Purging – Cycle Assessment

Step: 1 Purge Cycle Assessment

$$\frac{Y_c}{Y_o} = \left(\frac{P_l}{P_h}\right)^c$$

Step: 2 Mass of gas required

$$M_{cycle} = \frac{c\, V_E MW}{RT}(P_h - P_l)$$

Y_c – Final contaminant mole concentration
Y_0 – Initial contaminant mole concentration
P_l – Absolute pressure at Low pressure part of cycle
P_h – Absolute pressure at High pressure part of cycle
c – Number of purging cycles
M_{cycle} – Mass of clean gas required
V_E – Equipment volume to be purged
MW – Clean gas molecular weight
R – Ideal gas constant
T – Temperature

Common practice to add +1 cycle to account for poor mixing

Hydrocarbon processing, How to calculate purge gas volume, D.F. Schneider, Stone & Webster Engineering., Houston, 1993.

Purging – O_2 Impurity

Step: 1 Total no. of contaminant moles in Tank

$$n = \left(\frac{PV}{RTZ}\right)$$

Step: 2 Total no. of O_2 moles in Tank

$(O_{2\,(Final)\%}) * ($ Total Qty of moles in Tank)

Step: 3 Total O_2 Impurity in μ mol/mol

$$\frac{Total\ no.of\ O_2\ \text{moles in Tank}}{Total\ no.of\ contaminants\ in\ Tank}$$

n – no. of moles

P – Tank Pressure

V – Volume of the tank

R – Ideal gas constant

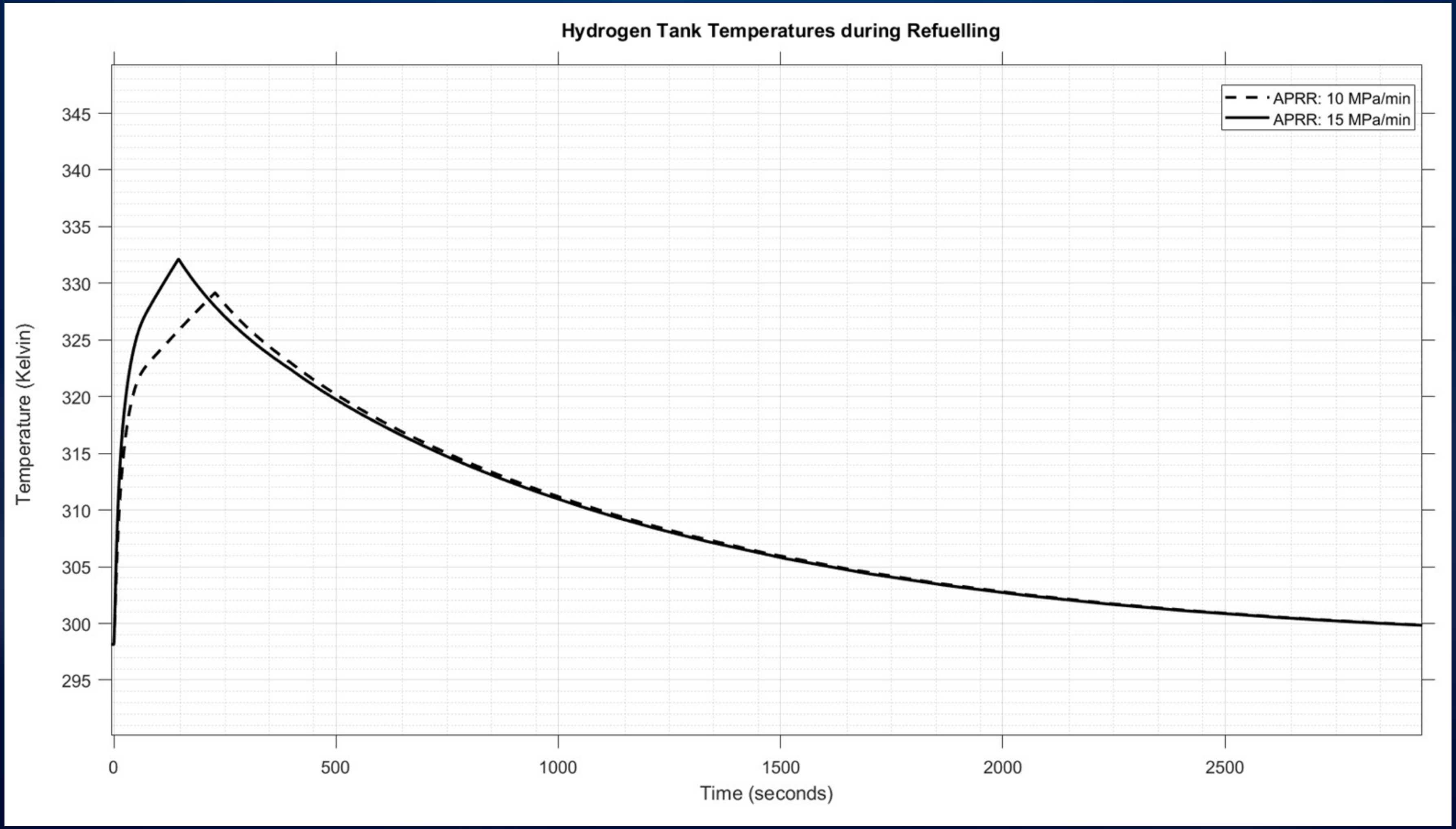
T – Temperature

Z – compressibility factor

A drop of water is approximately 2800 micromoles

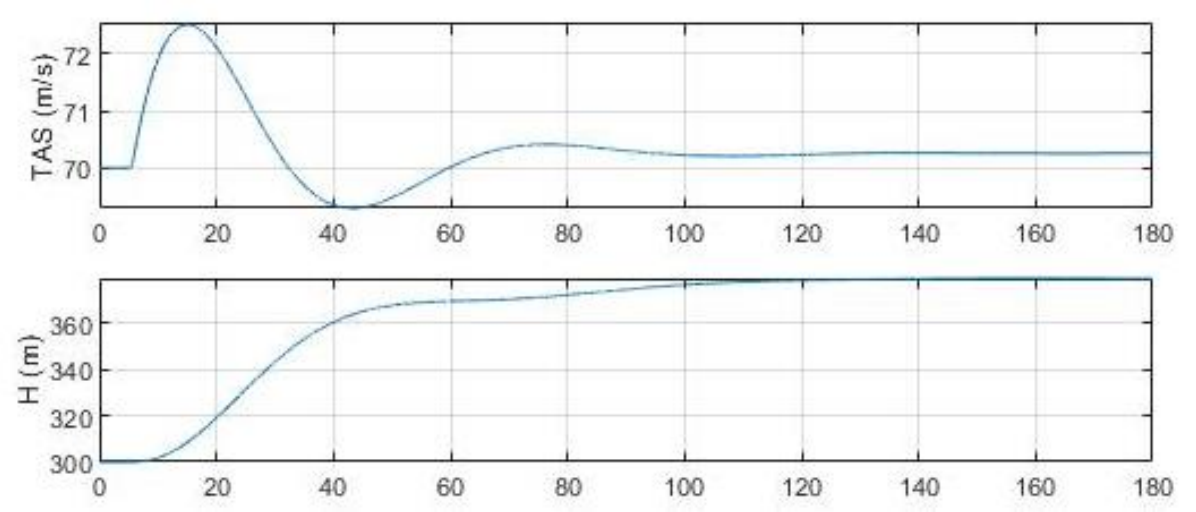
Hydrocarbon processing, How to calculate purge gas volume, D.F. Schneider, Stone & Webster Engineering., Houston, 1993.

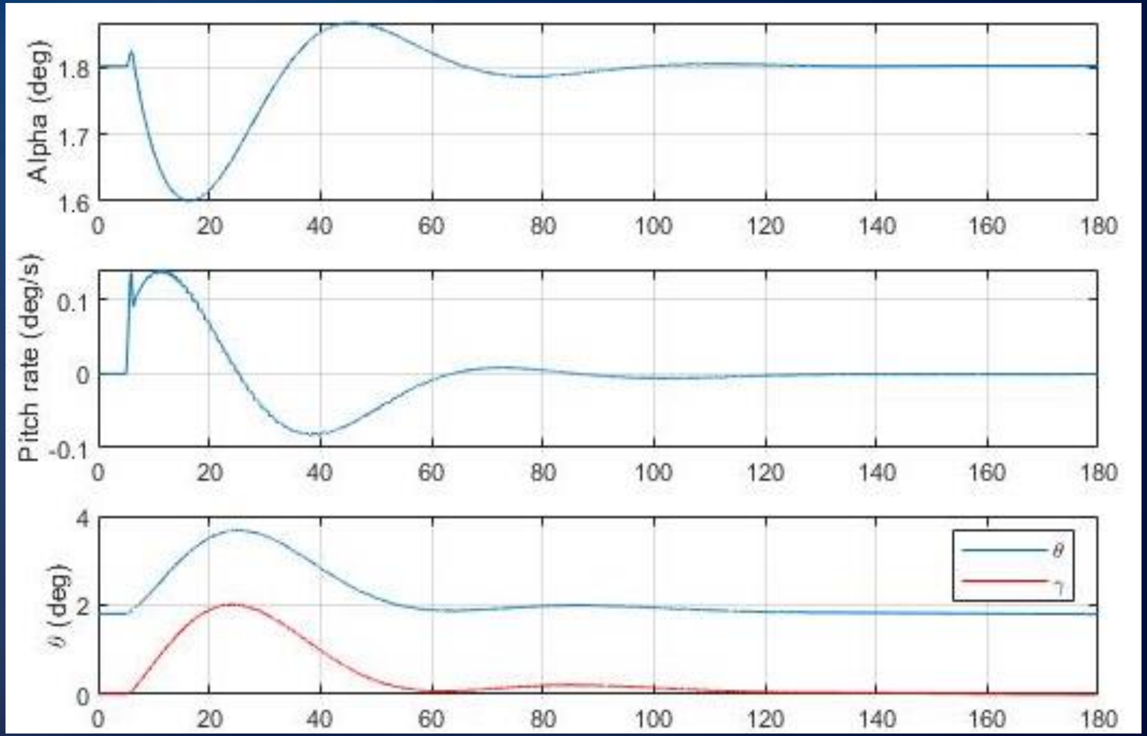
Fuel System – H_2 Fueling Temperatures



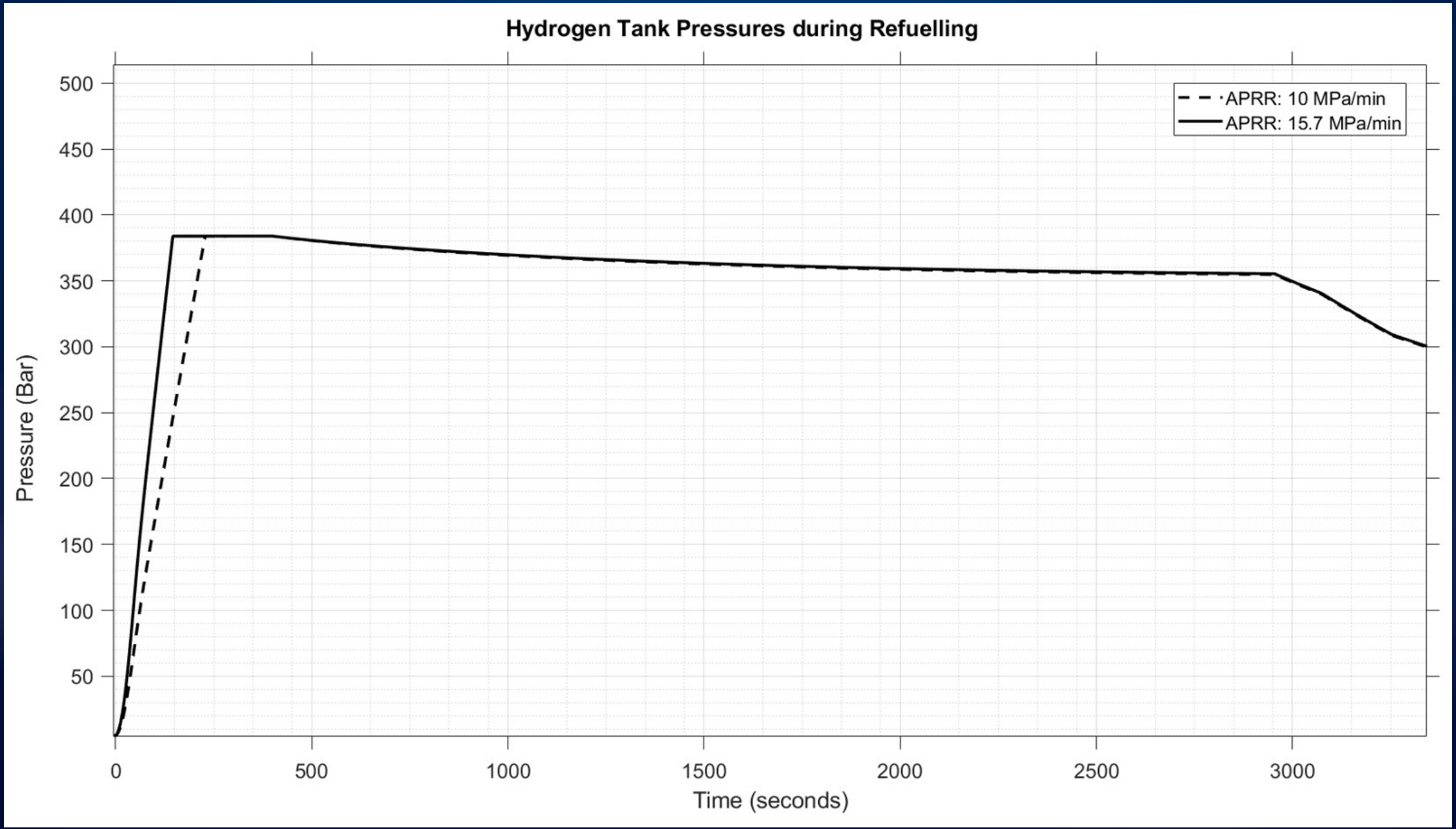
Cranfield **Aerospace Solutions**

Emergency Operation at 130KCAS



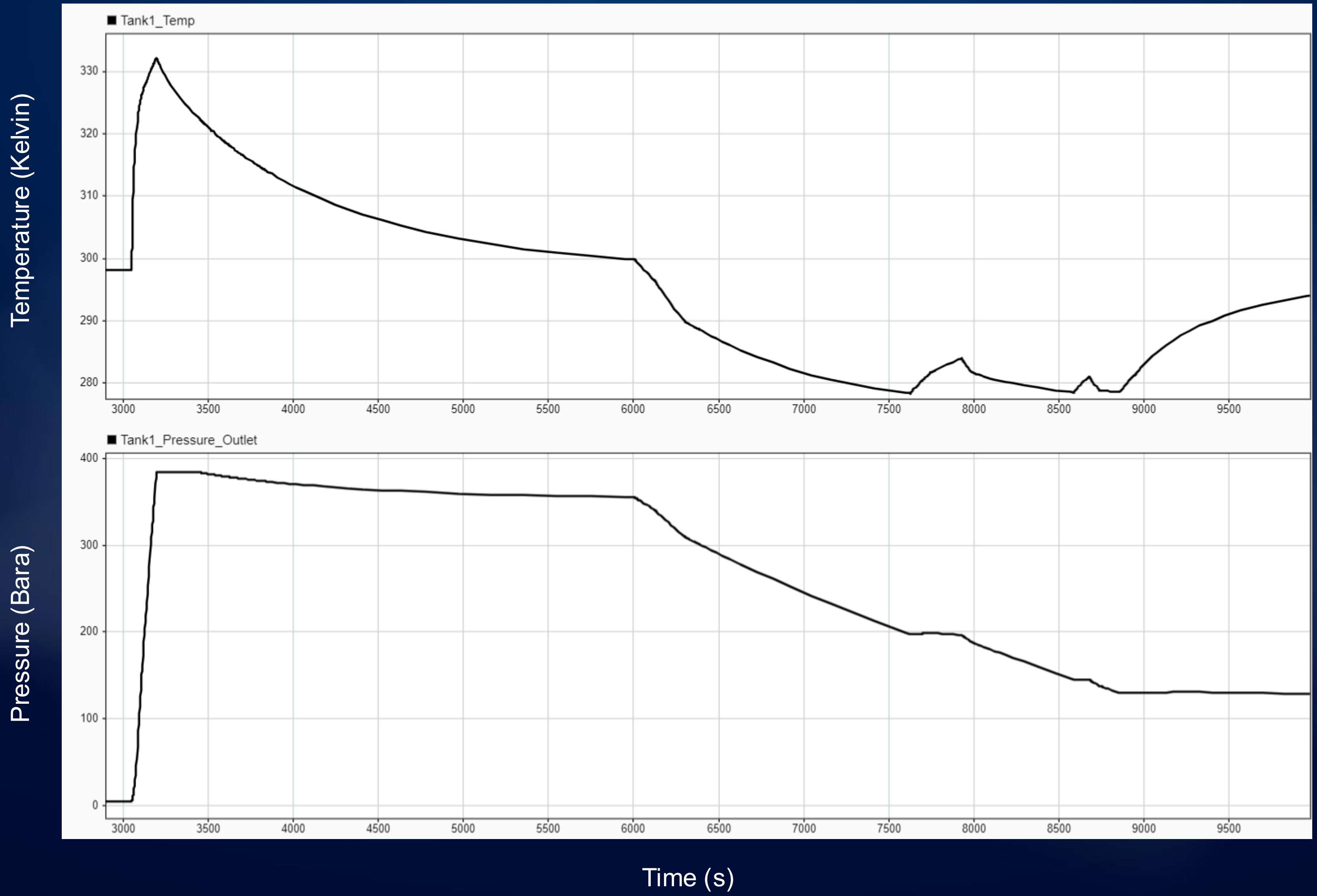


Fuel System – H_2 Fueling Pressures



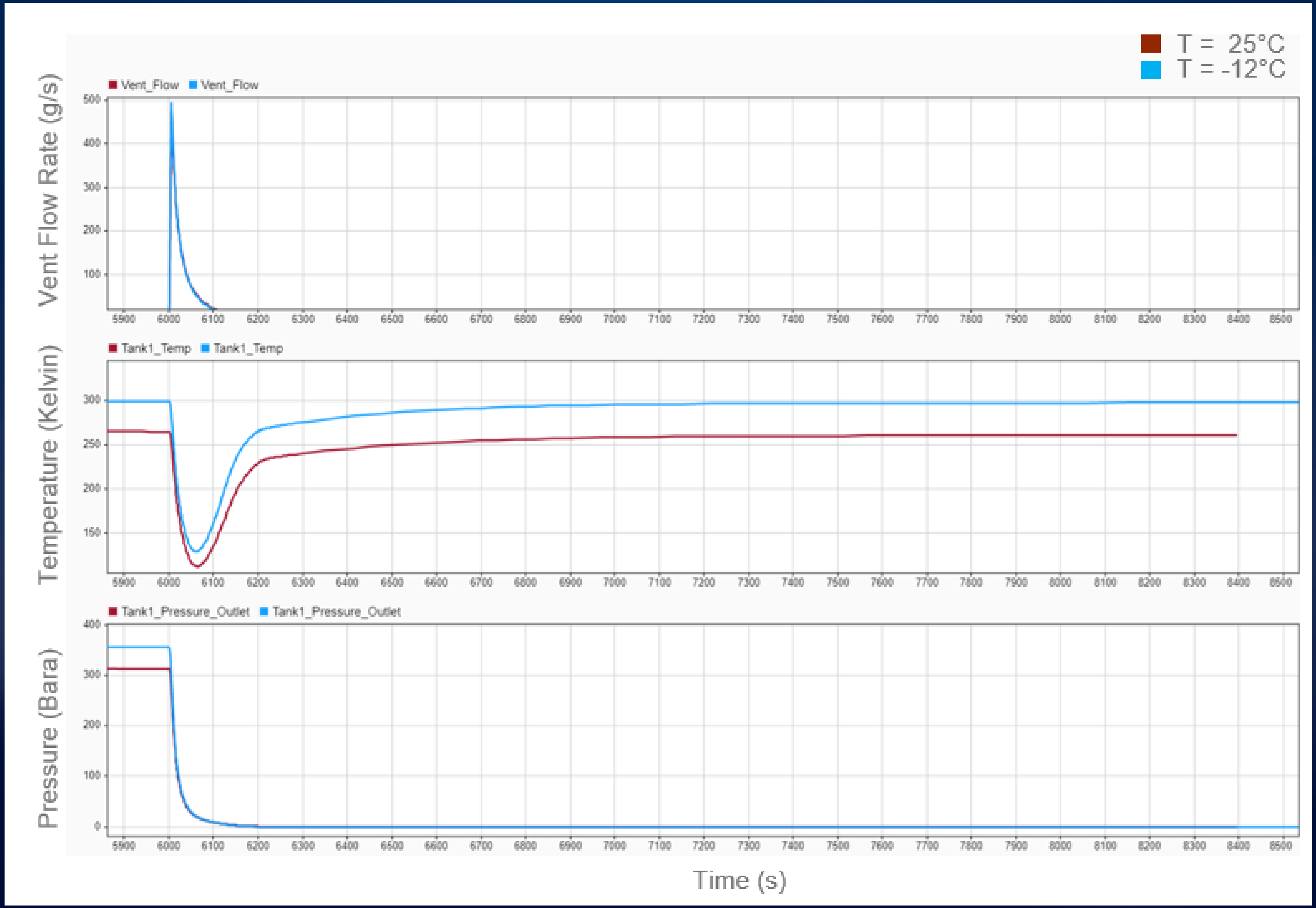
Cranfield Aerospace Solutions

Fuel System – Flow of H2 into Fuel Cell



Cranfield **Aerospace Solutions**

Fuel System – Venting



Cranfield **Aerospace Solutions**