

# Oxygen enrichment mechanisms of condensed phase air in liquid hydrogen environments

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Presented by Janet Welch



- European collaborative research project investigating the safety of liquid hydrogen (LH<sub>2</sub>) transfer technologies
- 3-Year project
- 8 European Partners



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## Introduction

- The hazard of oxygen enrichment of a hydrogen atmosphere is well known.
- Experimental evidence of an oxygen enriched environment leading to an explosion was seen at the HSE in 2014 and was presented at ICHS 2021.\*



Condensed air following  
liquid hydrogen release

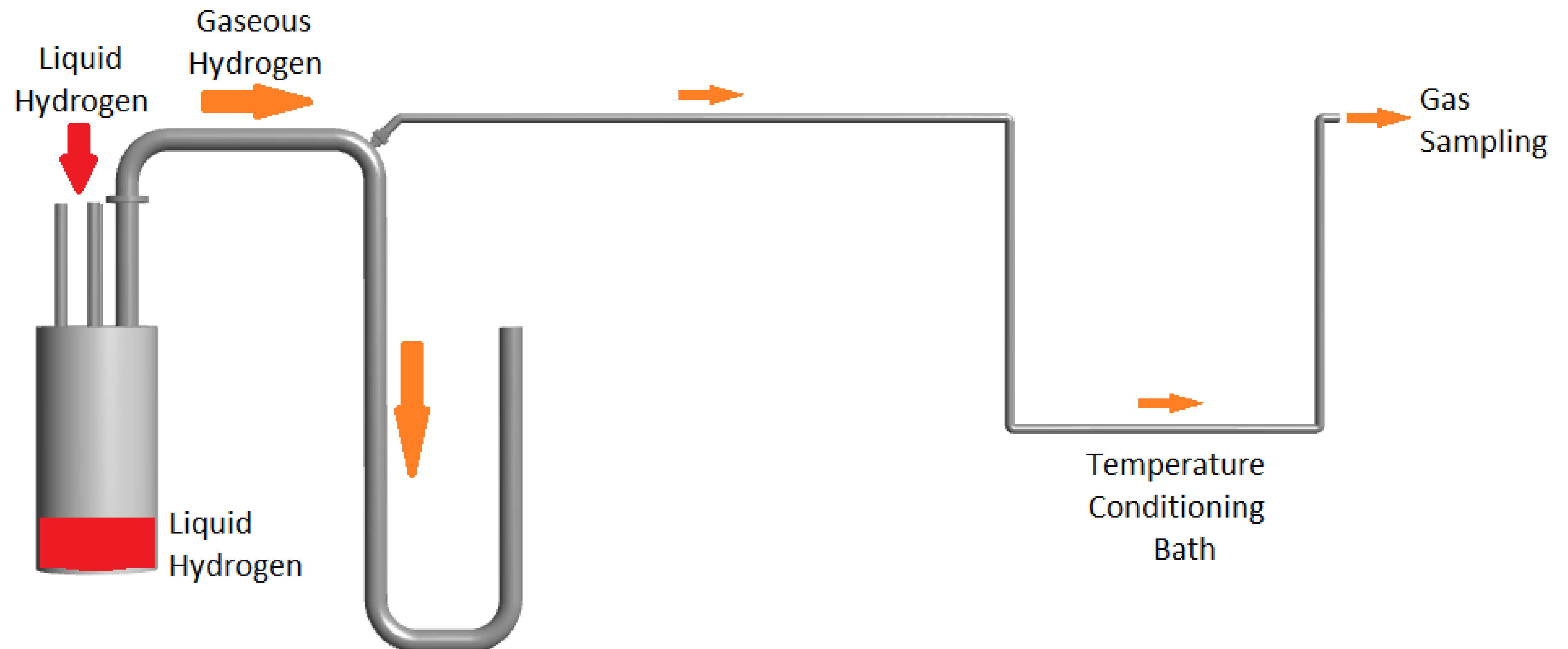


Comparison between fireball caused by (a) the initial  
flash fire and (b) the secondary explosion.

\* Atkinson G. (2021) Condensed phase explosions involving liquid hydrogen. International Association on Hydrogen Safety: International Conference on Hydrogen Safety.

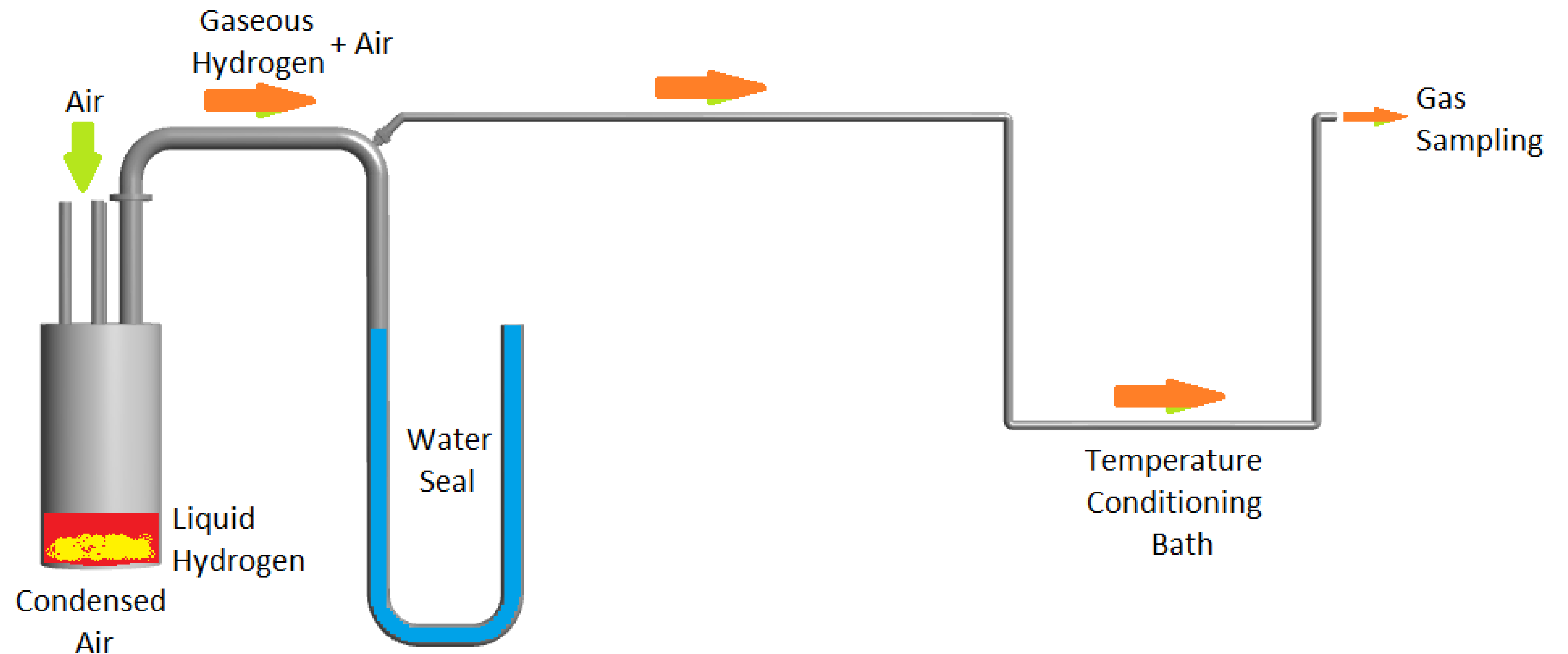
## Experimental Methodology – Stage One

- Container surrounded by foam which is temperature conditioned by multiple hydrogen fills to reduce the hydrogen evaporation rate before the final fill to level.



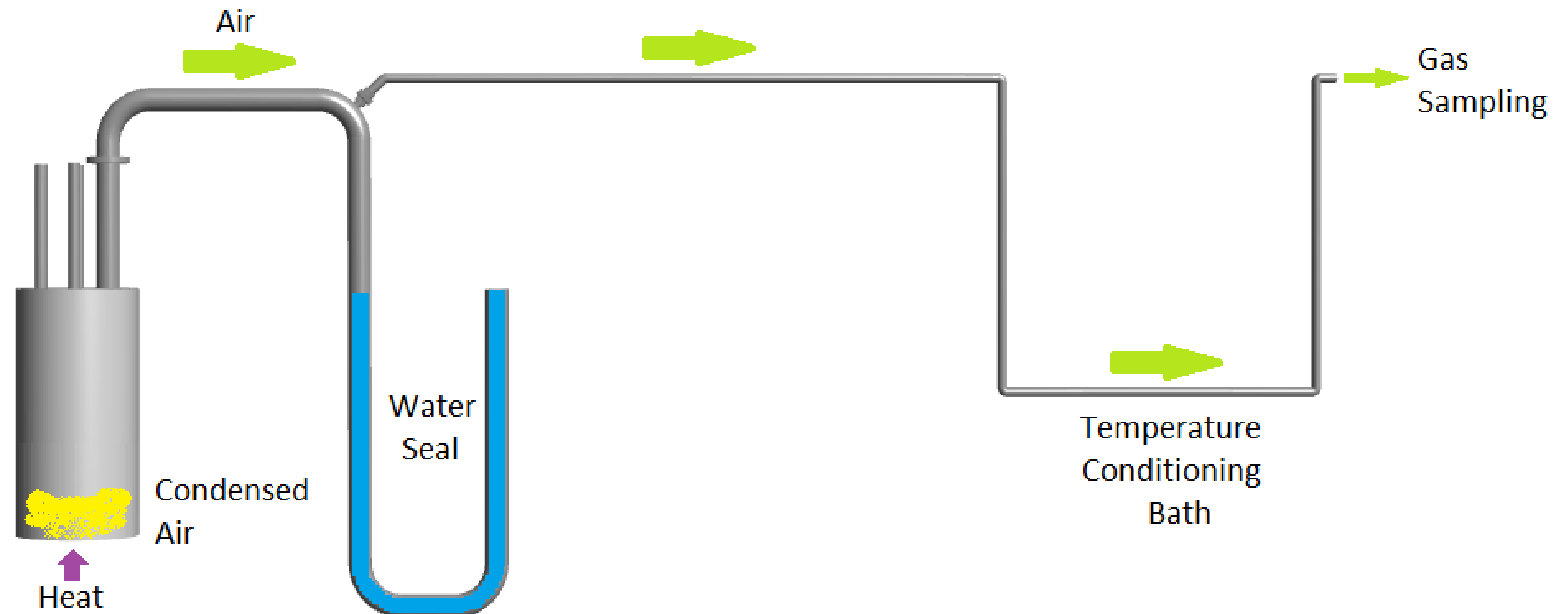
## Experimental Methodology – Stage Two

- Ambient bottled air was introduced using a flow controller, the hydrogen takes heat energy from the air, condensing the air while the liquid hydrogen boils.



## Experimental Methodology – Stage Three

- Stage Three started once there was no hydrogen detected in the vapour phase.
- The condensed air was heated and boiled off.



## Results

- Three tests were undertaken.

Test	1	2	3
Liquid hydrogen fill level (dm <sup>3</sup> )	13	27	54
Calculated volume of liquified oxygen (dm <sup>3</sup> )	0.6	0.9	1.5
Calculated volume of liquefied nitrogen (dm <sup>3</sup> )	3.8	6.0	9.7

- Three distinct periods of liquid and vapour phase oxygen enrichment were observed, to be discussed.
- This presentation discusses the evidence observed for the phase changes associated with the air components and the periods of oxygen enrichment.

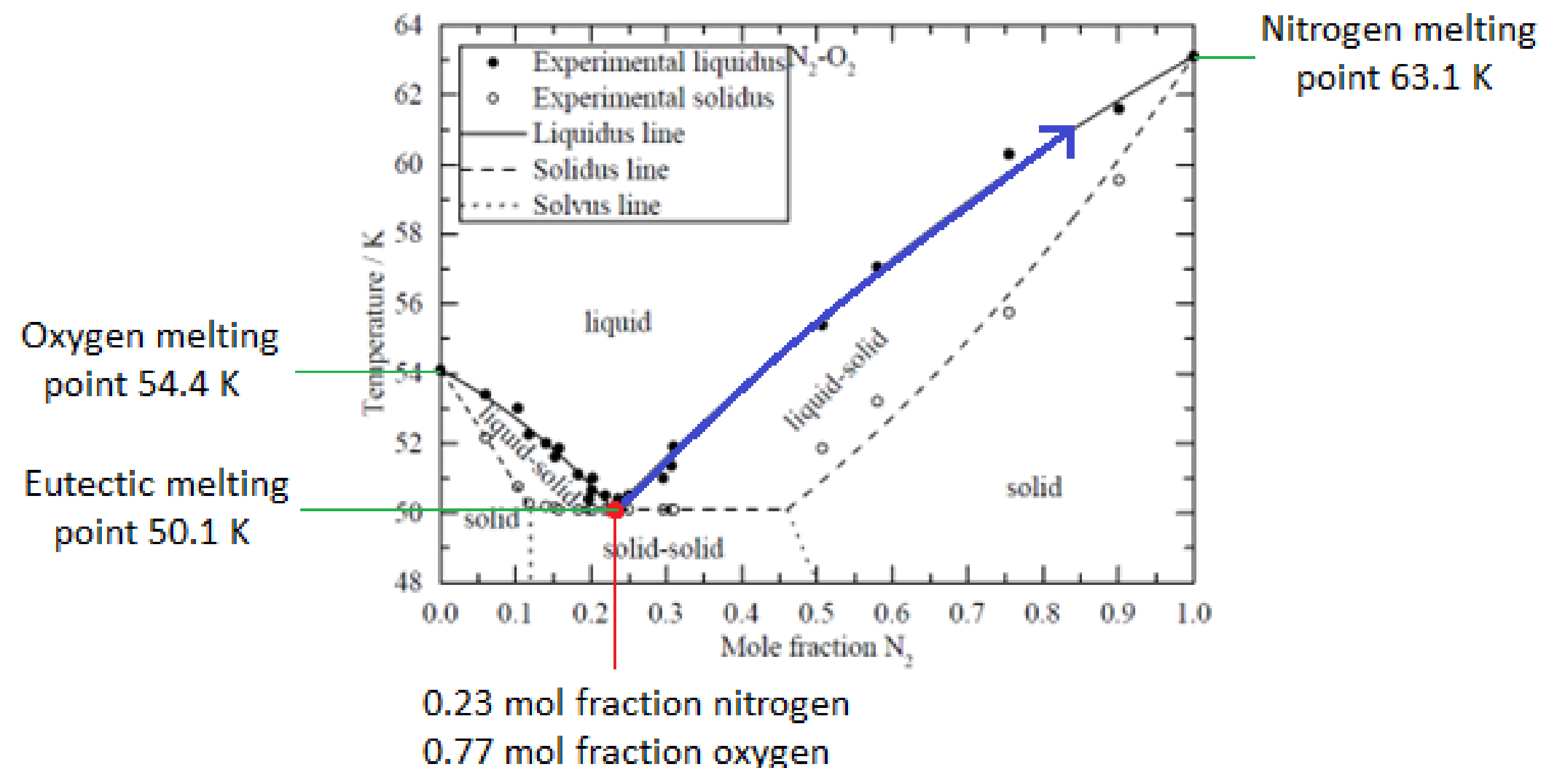
## **Liquid Oxygen and Nitrogen form a Eutectic Mixture**

- Liquid oxygen and liquid nitrogen are completely miscible with each other and form a eutectic mixture.
- During the air freezing process impure crystals are formed, when nitrogen crystallises up to 20 % of the nitrogen atoms within the crystal structure can be replaced with oxygen atoms.\*
- In this work we are only interested in the process of eutectic melting.
- A eutectic solid is a solid mixture of two or more components that melts as a mixture at a temperature below each components pure melting point.

\* Sihachakr D., Loubeyre P. (2004)  $O_2 / N_2$  mixtures under pressure: A structural study of the binary phase diagram at 295 K. Physical Review B. 70(13):134105

## Explaining Eutectic Melting using the Oxygen and Nitrogen Binary Phase Diagram

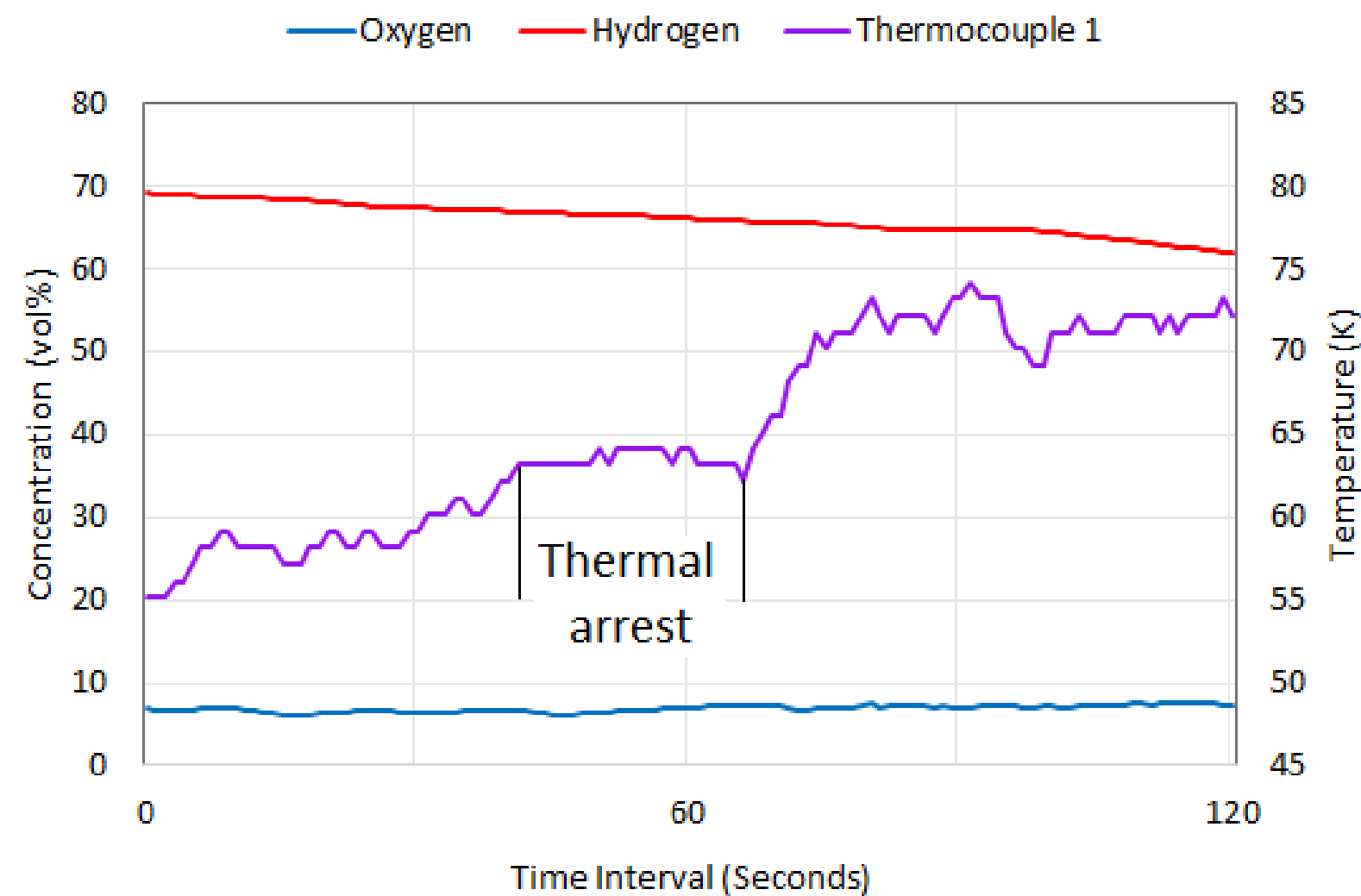
- As the oxygen starts to melt it dissolves some of the solid nitrogen into the liquid phase. This impure liquid has a lower boiling point, the eutectic melting point (red dot).
- The mixture melts at the eutectic point until all the minor component, oxygen, has melted.
- As the remaining solids melt the melting point increases along the liquidus line (blue arrow).



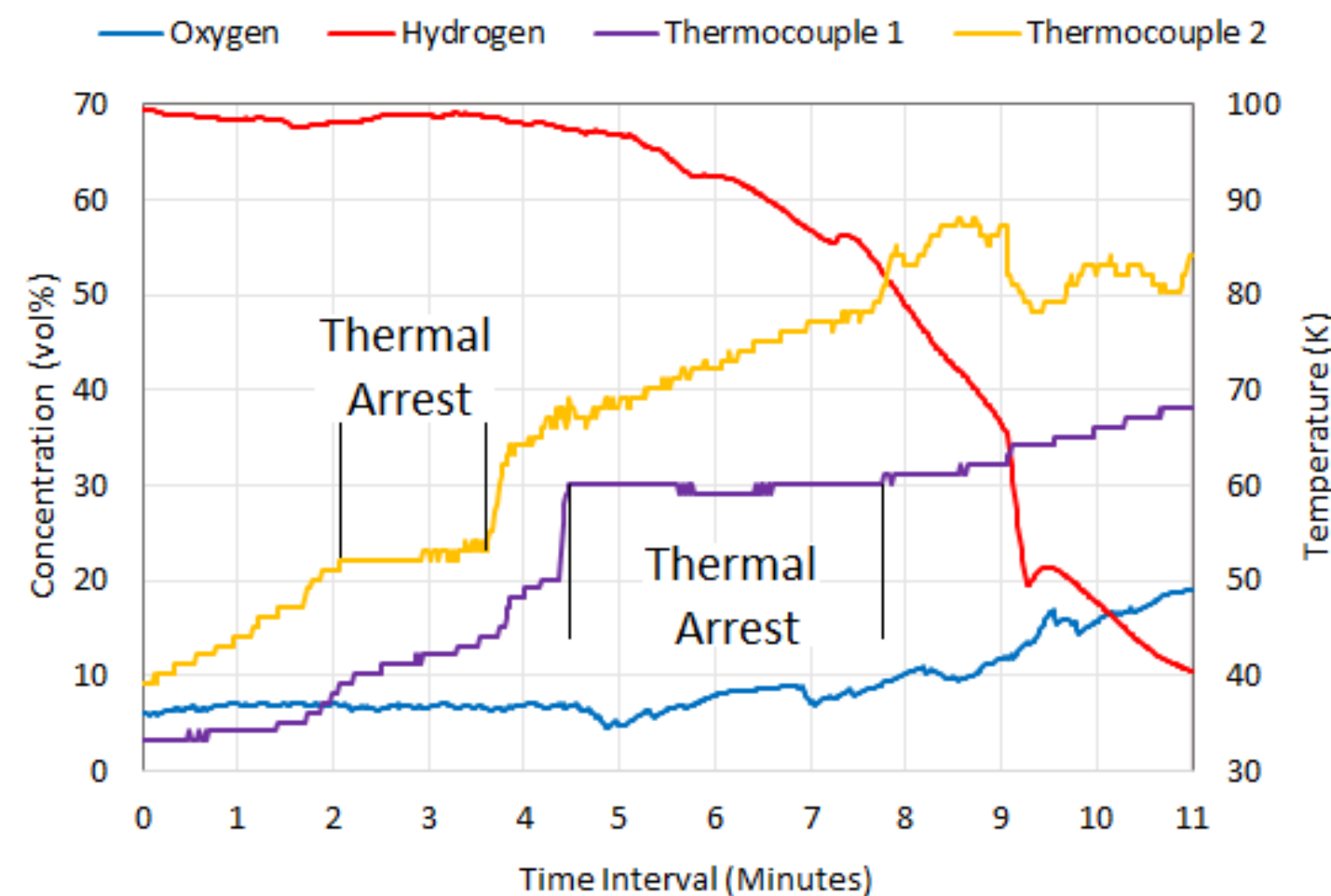
## Evidence of Eutectic Melting Observed at the End of Stage Two

- At the end of stage two as the last of the liquid hydrogen boils-off the temperature(s) at the bottom of the container start to rise.
- ‘Warm’ air is still being introduced at the top of the container.
- There is still hydrogen present in the container vapour space.

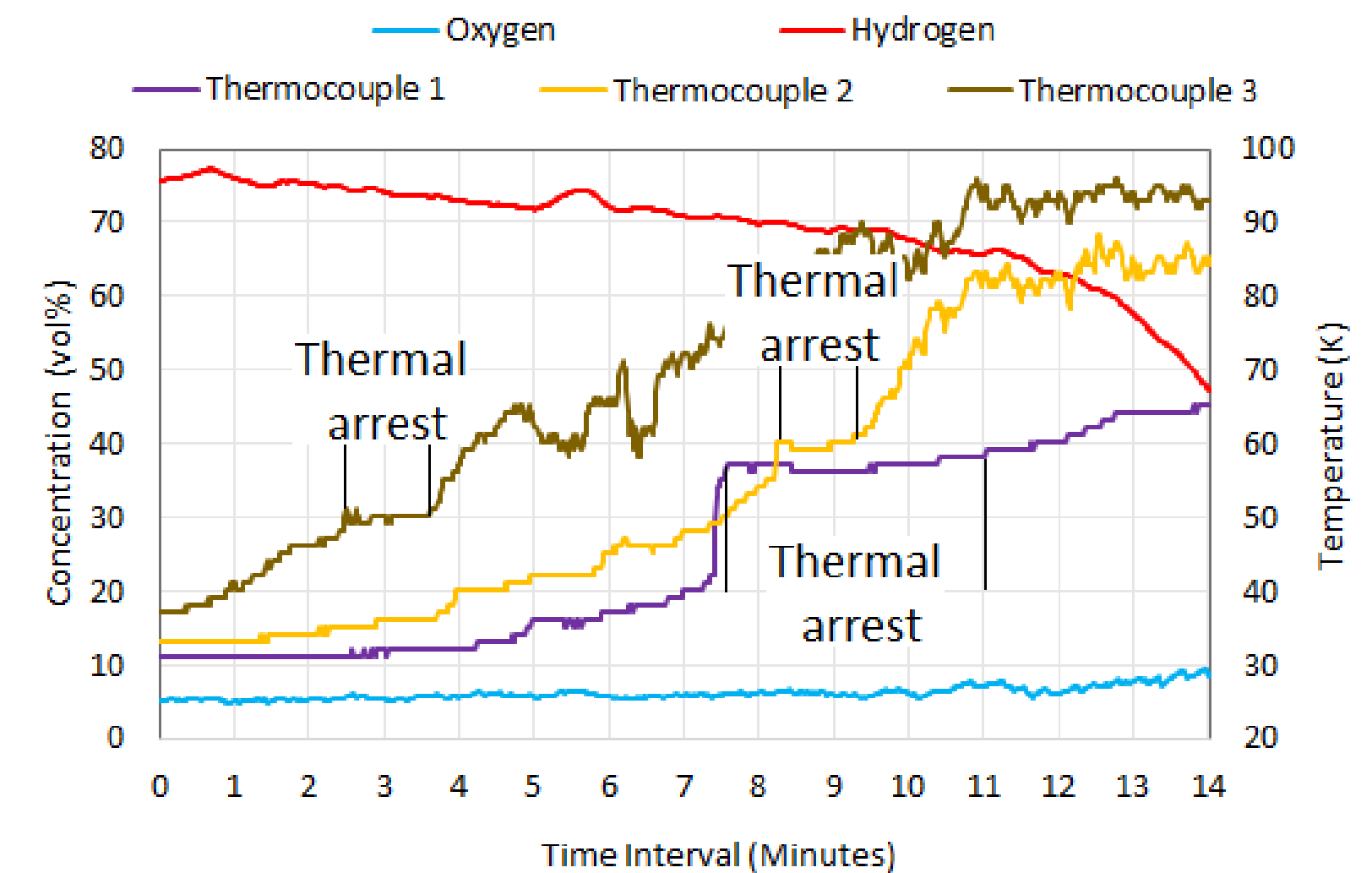
### Test 1



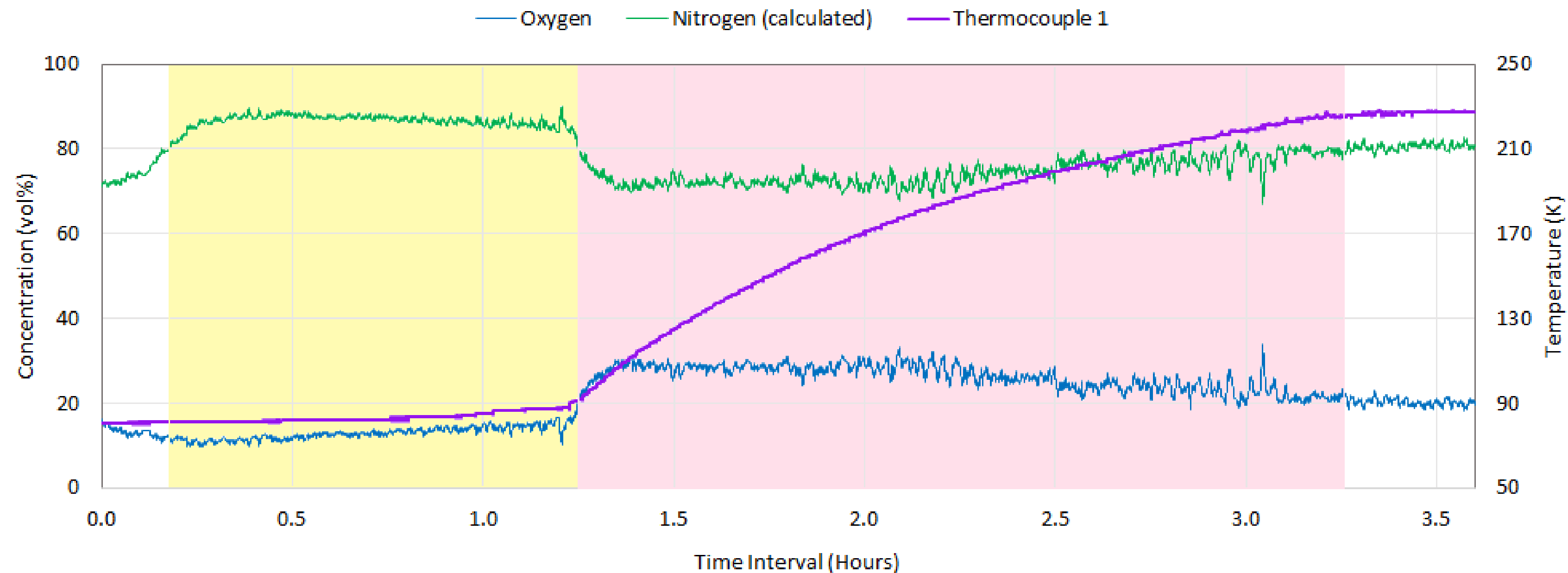
### Test 2



### Test 3



## Test 1 - Evidence of Oxygen Enrichment of the Liquid and Vapour Air Phase during Stage Three.



- The last trace of hydrogen in vapour phase was observed just before the yellow box.
- Yellow box = Vapour phase oxygen deficient, liquid phase becomes oxygen enriched.
- The liquid phase is calculated to be at peak oxygen enrichment level at the yellow/pink boundary.
- Pink box = Vapour phase oxygen enriched with the level of enrichment dropping over time.

## **Conclusions**

- Evidence for a complicated solid to vapour phase change system for solid air products has been observed in these tests. The system is characterised by 5 main periods.
  1. Pure eutectic melting of an oxygen and nitrogen mixture, resulting in an oxygen enriched liquid phase.
  2. Melting of the remaining solid nitrogen, diluting the oxygen enriched liquid phase.
  3. Boil-off from nitrogen, resulting in an oxygen enriched liquid phase.
  4. The oxygen enriched liquid phase boil-off, resulting in a period where both the liquid and vapour phase are oxygen enriched.
  5. The liquid phase ceases to be oxygen enriched, but the vapour phase continues to be oxygen enriched until it is dispersed from the liquid surface.

## Using Knowledge Gained in ELVHYS to Study ‘Real World’ Scenarios



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## Acknowledgements

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[ELVHYS EU project - Hydrogen Safety, Liquid Hydrogen Transfer](https://elvhys.eu/home)

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# Thank you. Questions?

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