



Experimental study of oxygen enrichment during liquid hydrogen releases

Janet Welch

16/09/2026



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Background

- The consequences of oxygen enriched liquid hydrogen mixtures was studied by NASA in the 1960's.
- Unexpected condensed phase explosions of liquid hydrogen have been observed in recent tests (ignited tests).

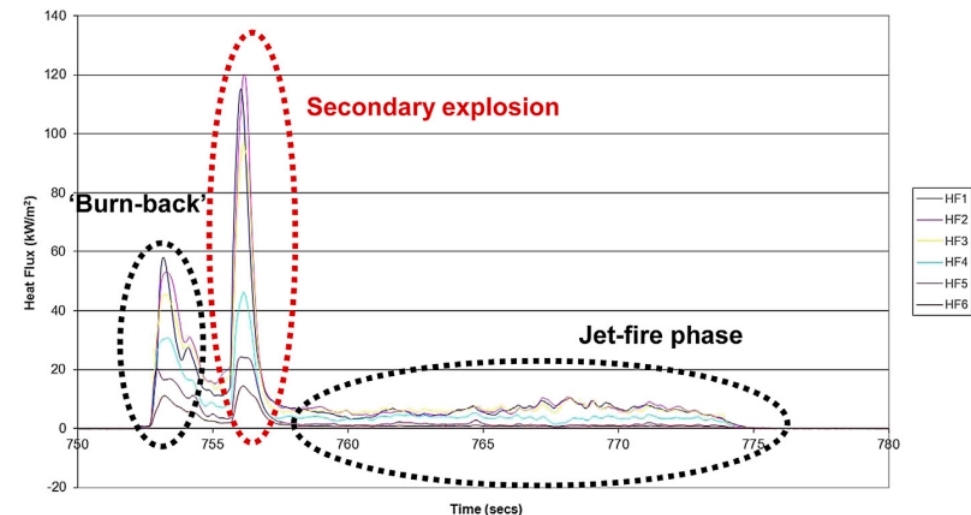
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HSE 2014



IR camera

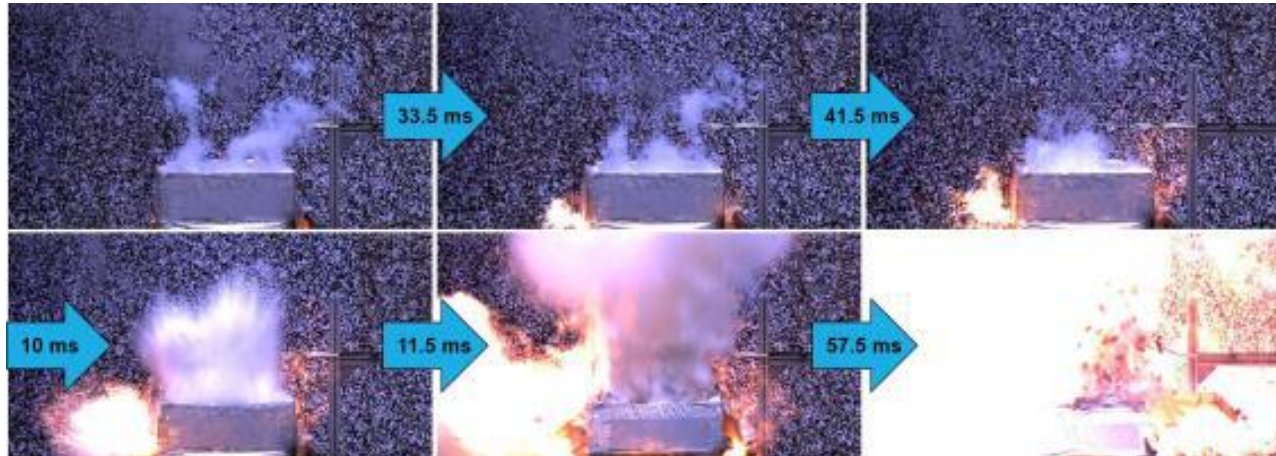


Radiometer data

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KIT 2020



High speed camera

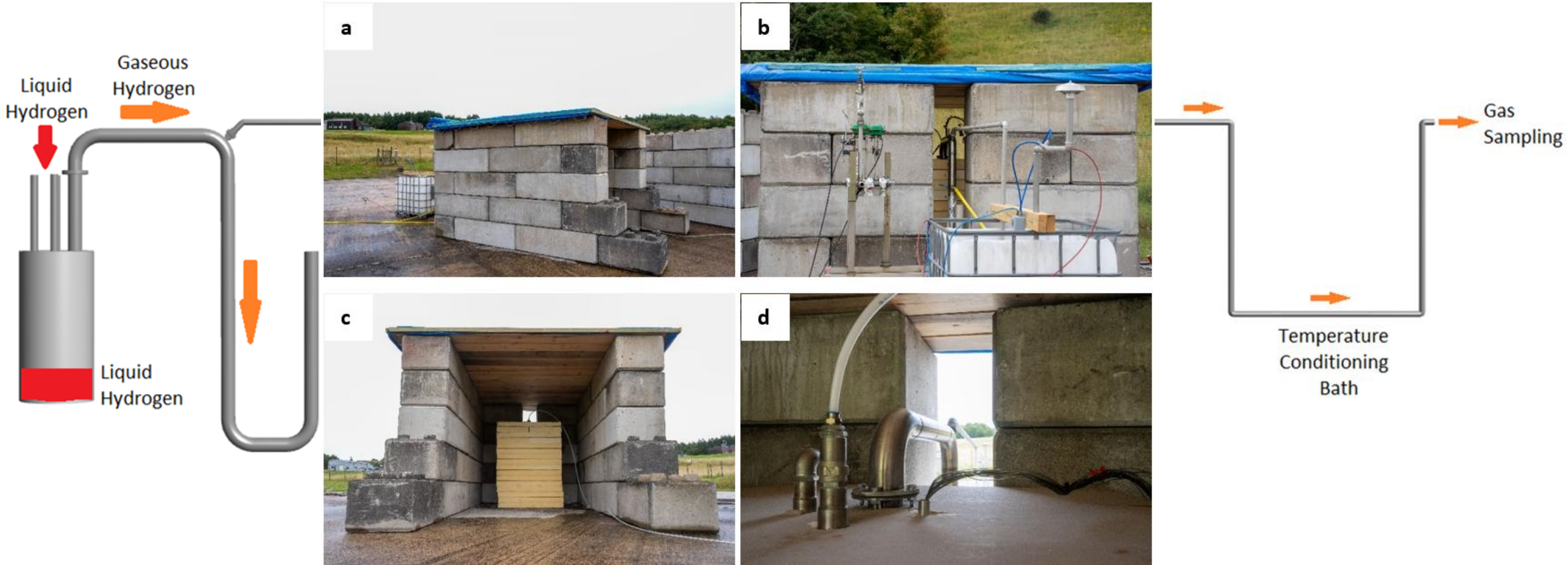


Photograph of damage

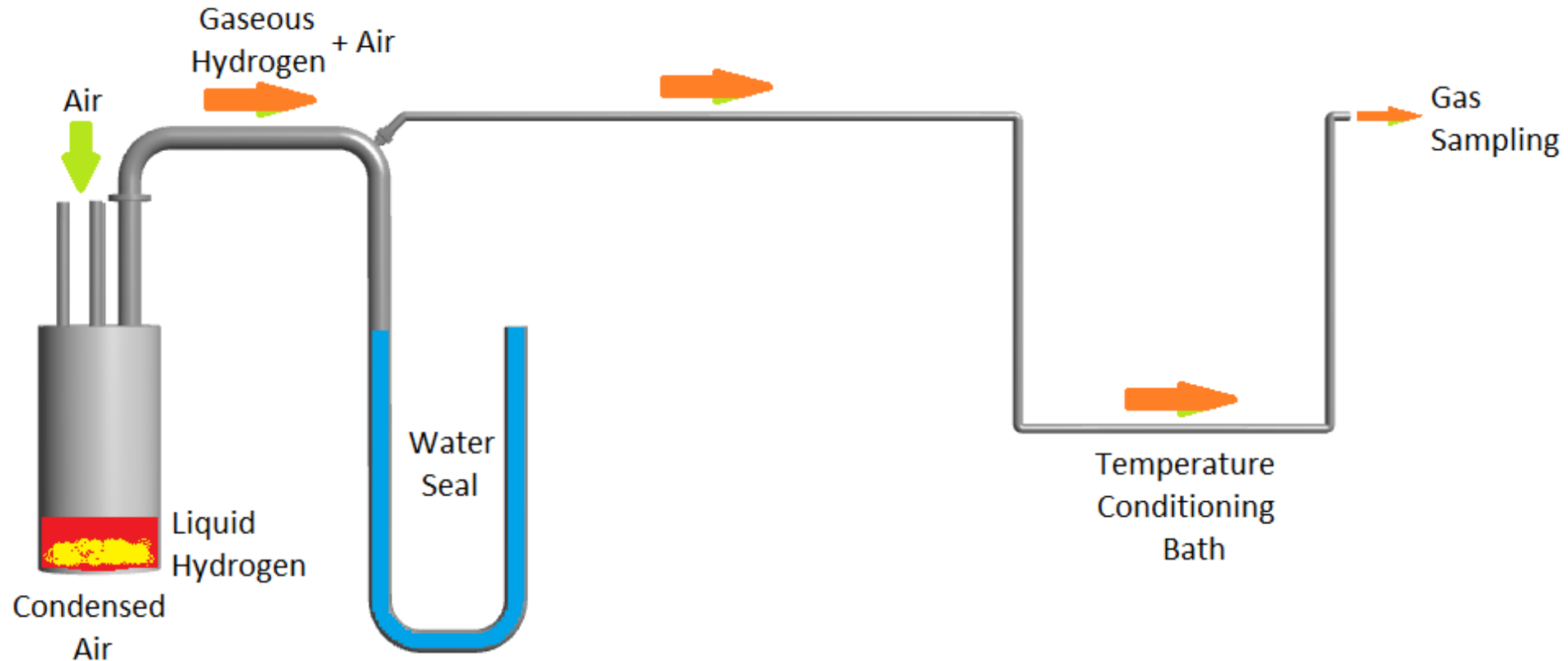
Background

- The only source of oxygen available during these tests was the surrounding air.
- Oxygen enrichment must have been due to the condensation of oxygen in air.
- These were just two tests out of around 20 tests undertaken. Repeat tests at HSE did not produce the same result.
- The probability of formation of an oxygen enriched liquid hydrogen mixture, where oxygen from condensed air was the only source of oxygen available, is unknown.

The experimental rig – Hydrogen fill

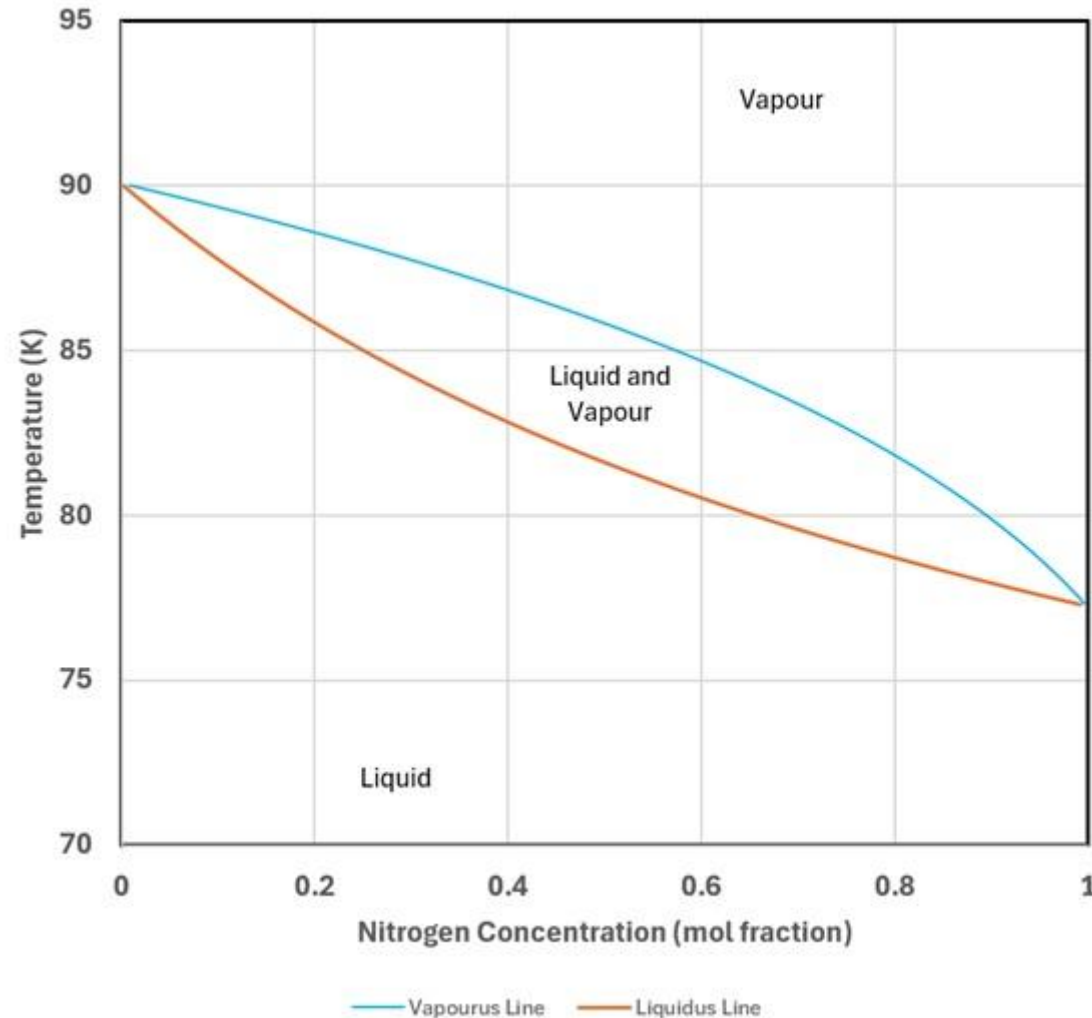


Condensation of air



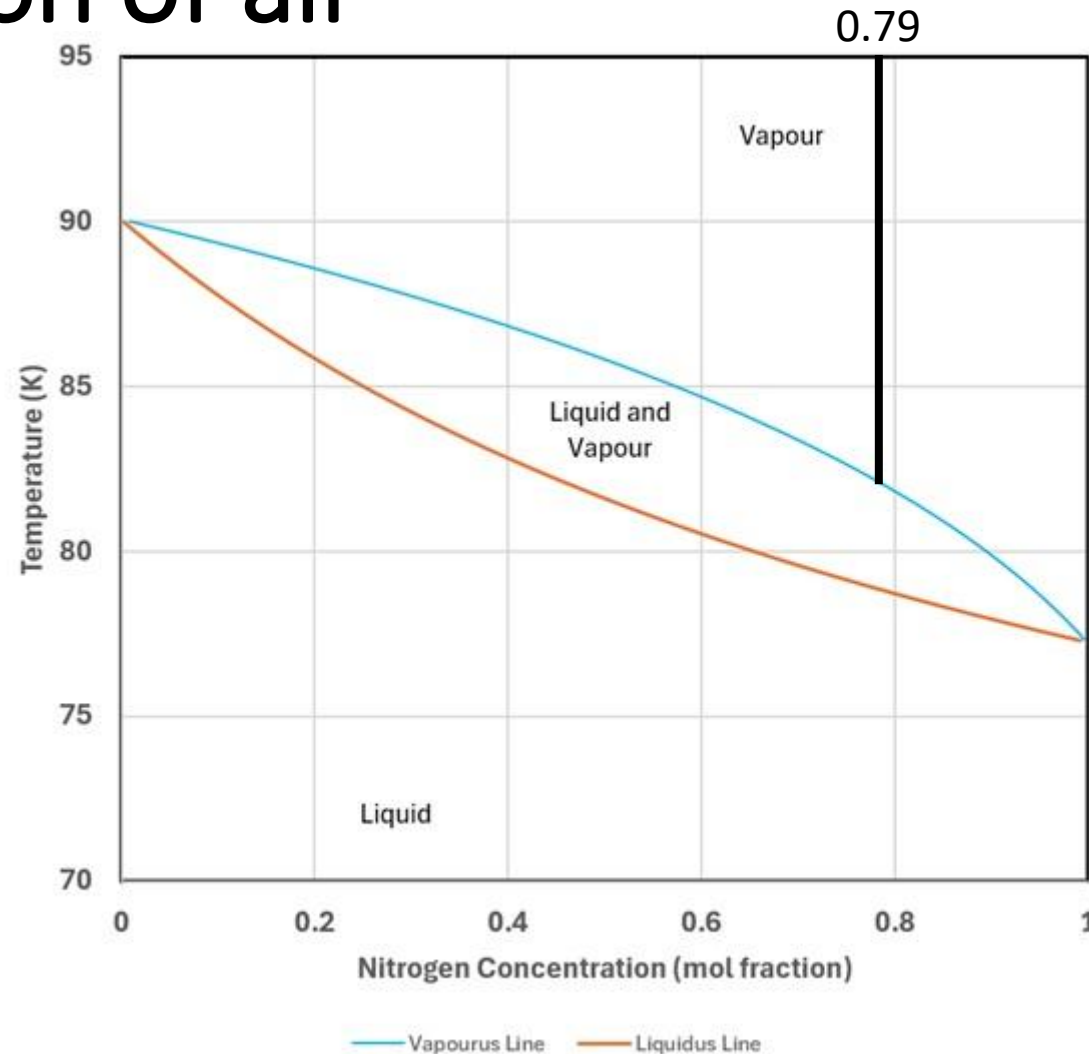
Possible oxygen enrichment during condensation of air

Nitrogen and Oxygen
Liquid and Vapour
Binary Phase Diagram



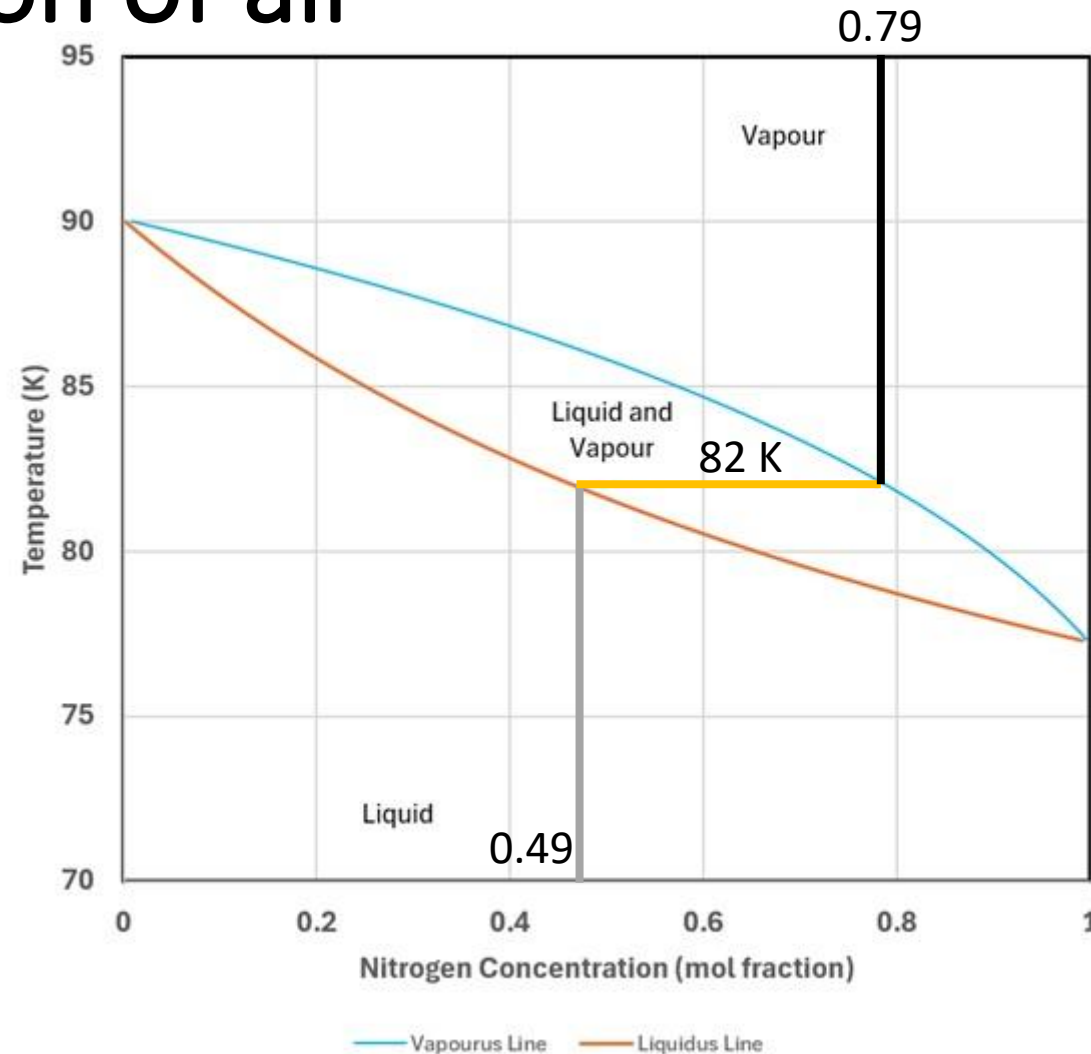
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Equilibrium Liquefaction



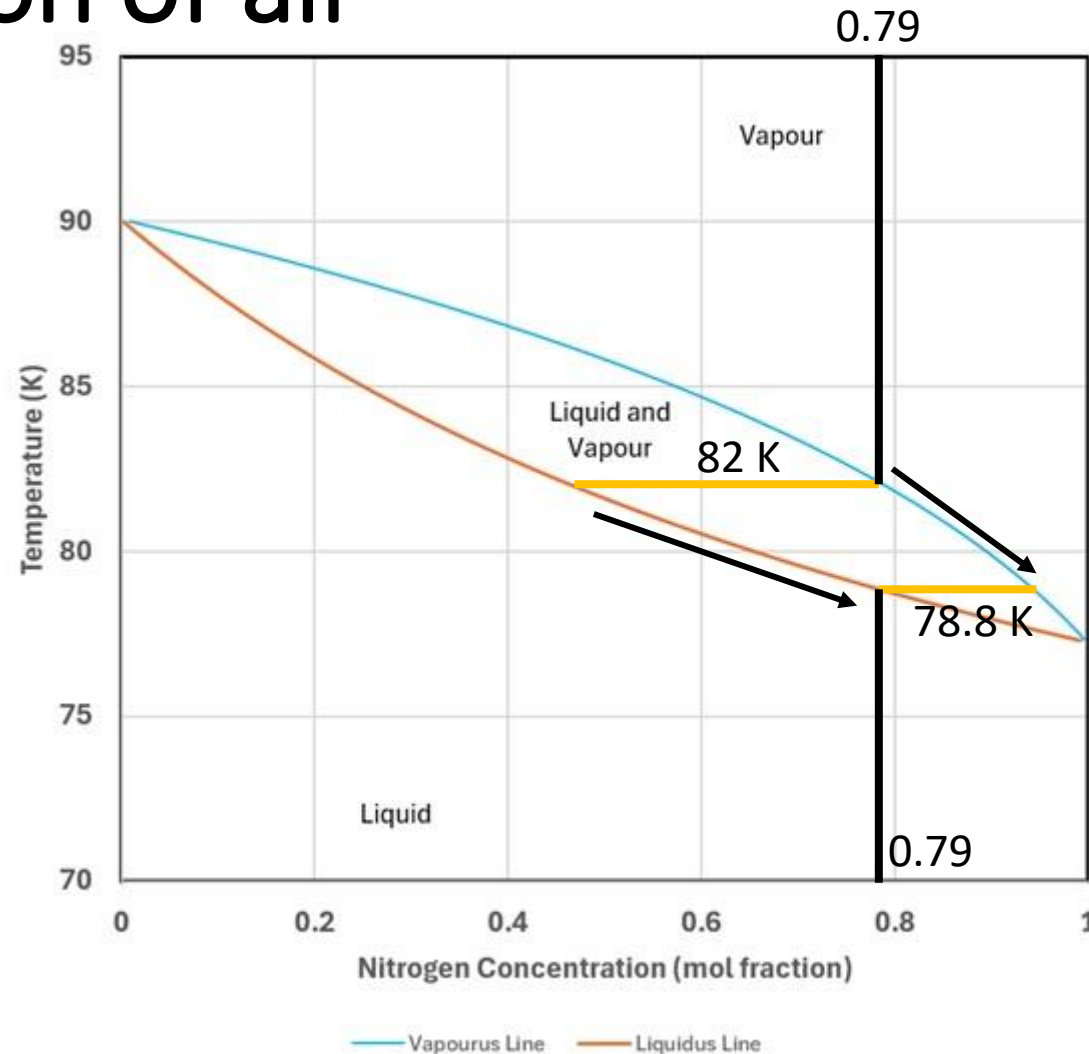
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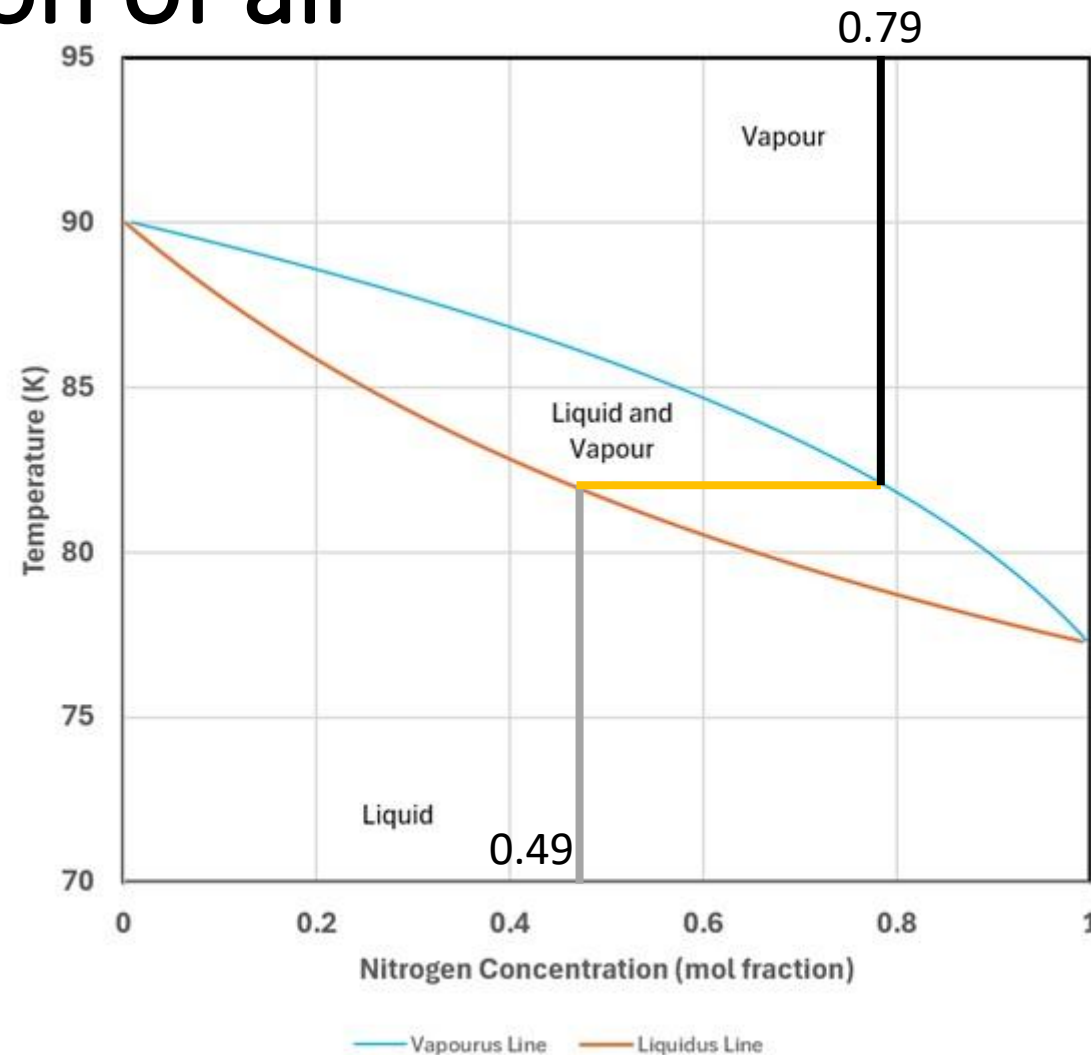
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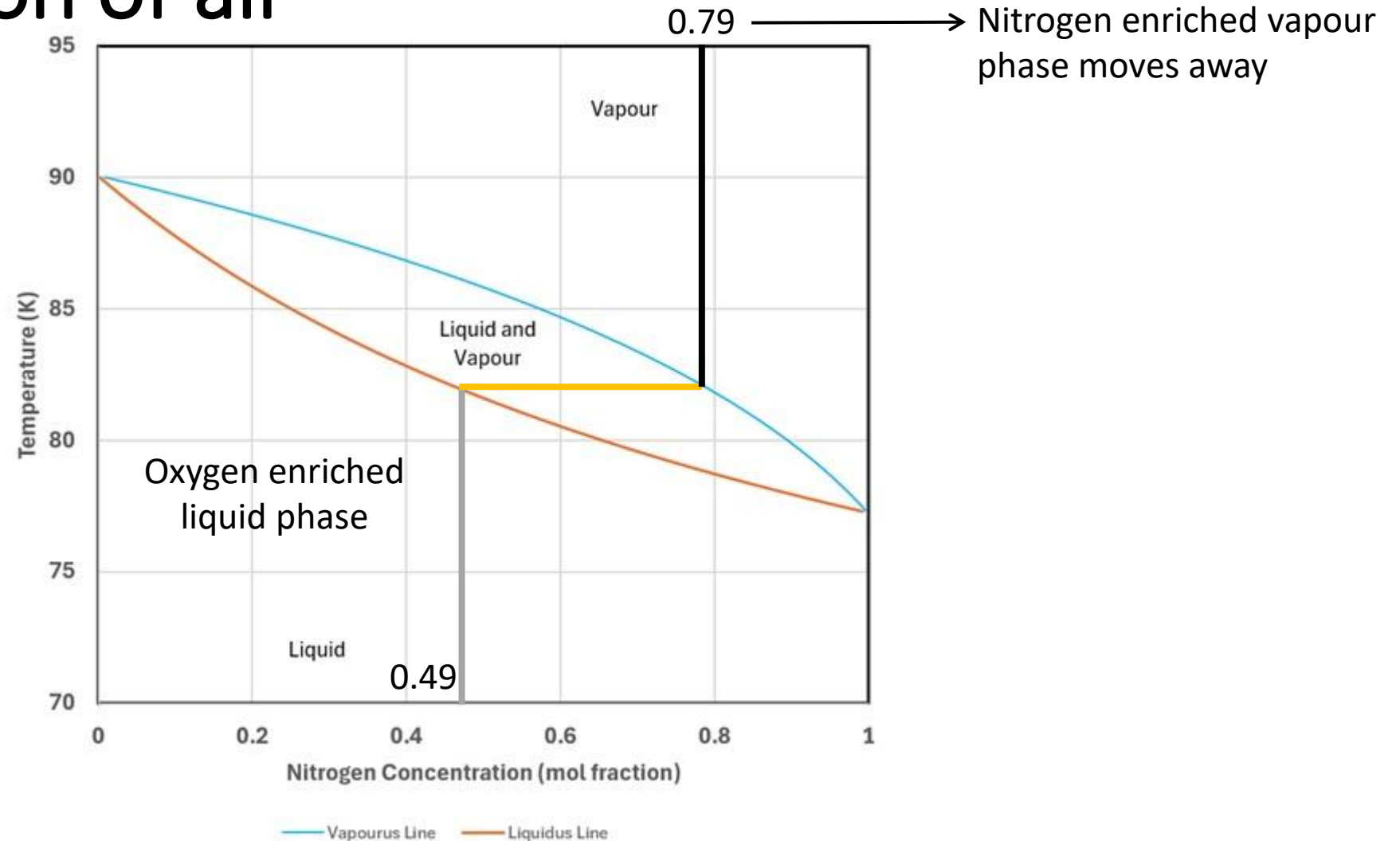
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Fractional Liquefaction



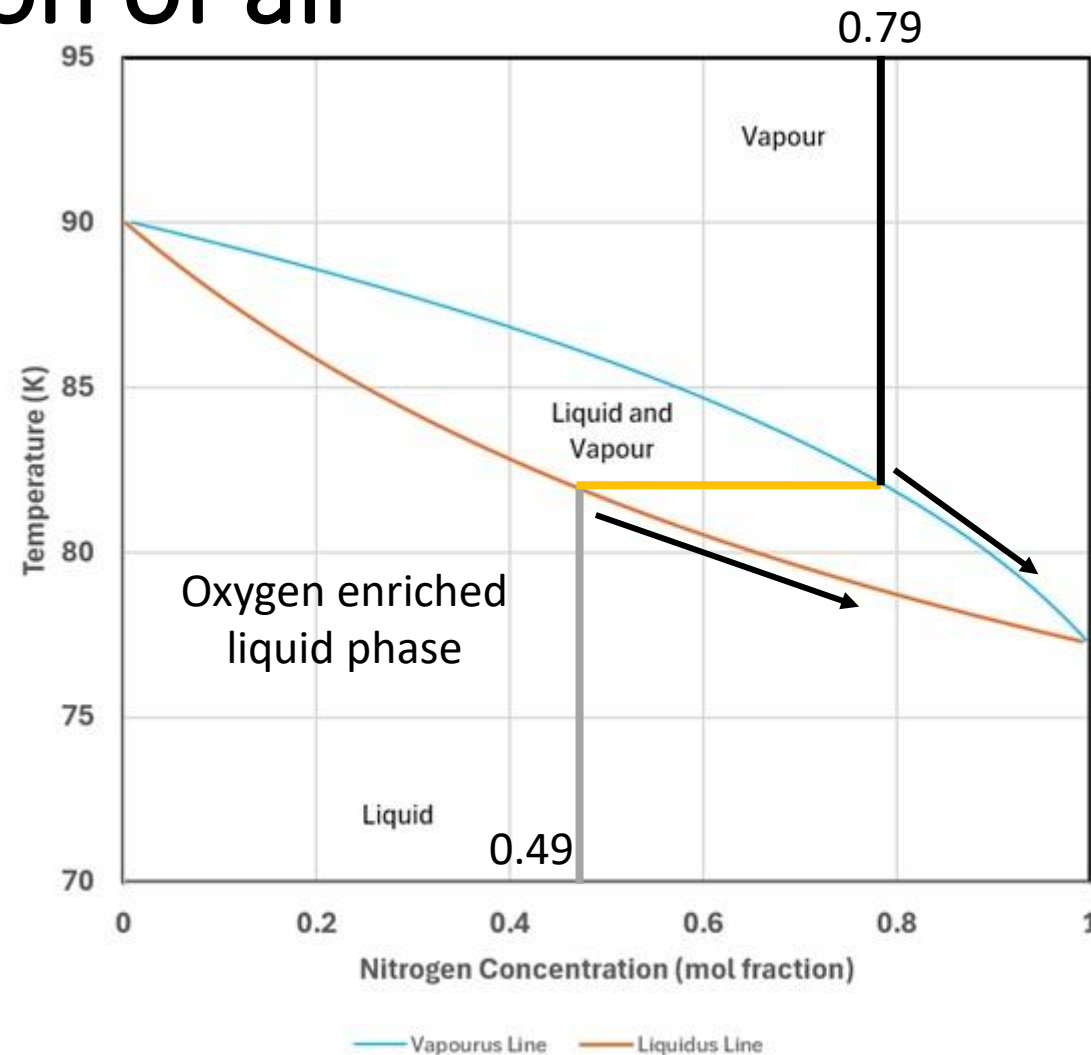
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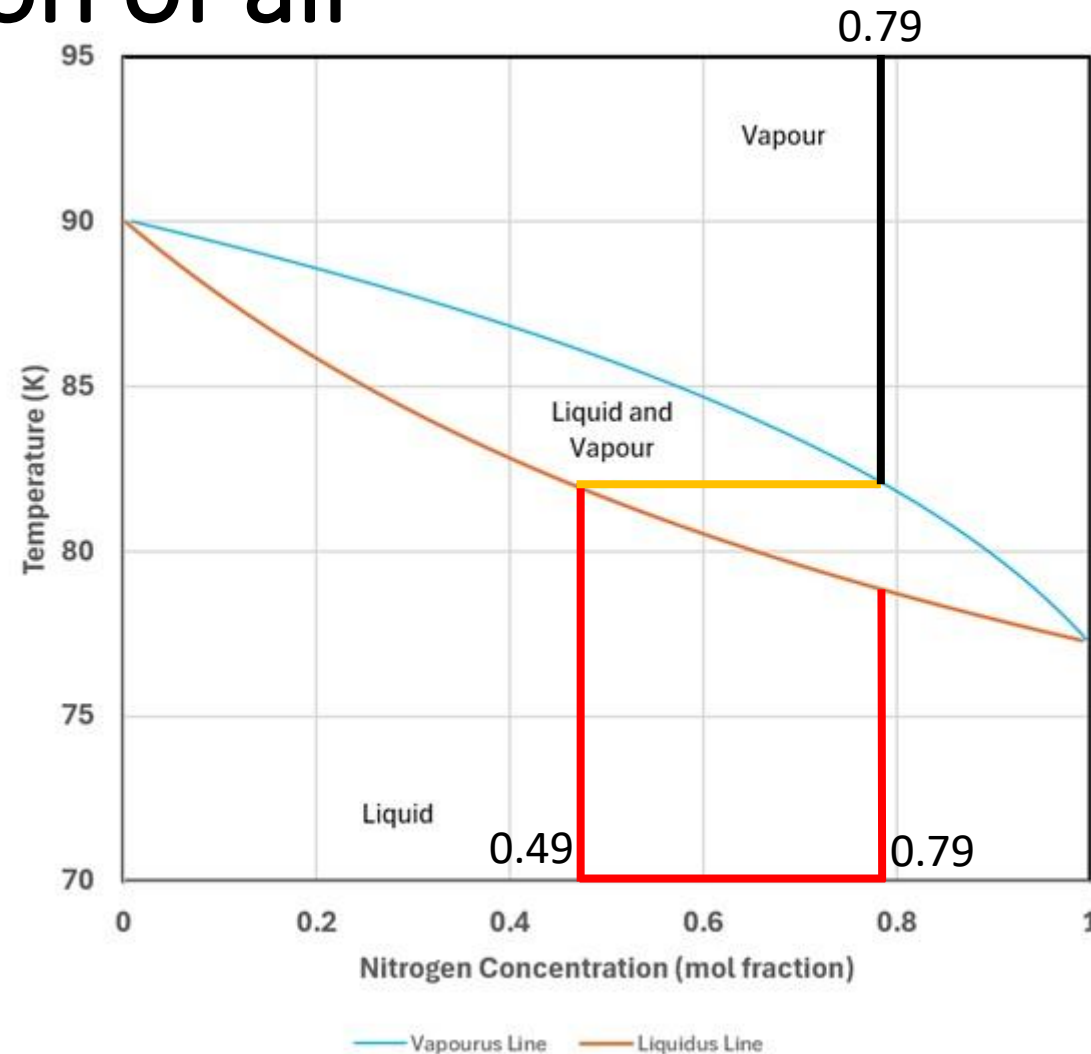
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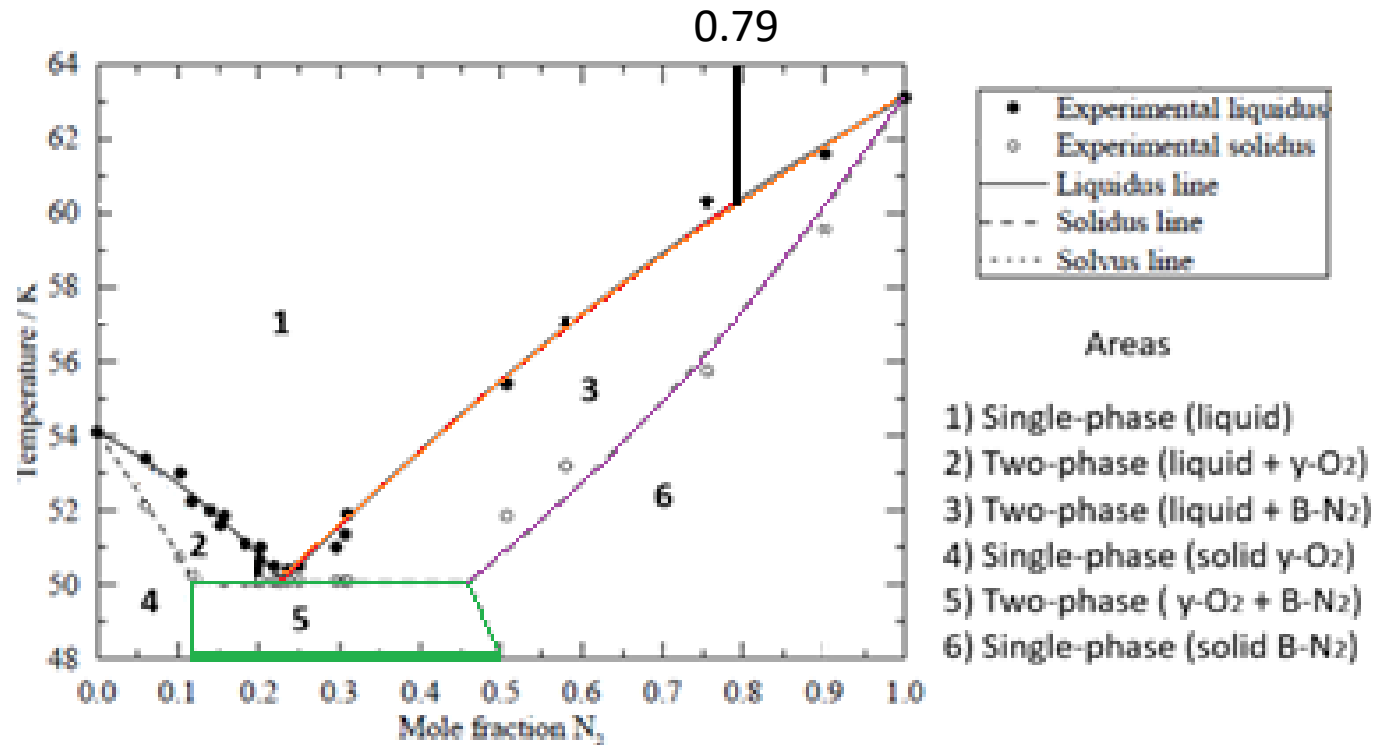
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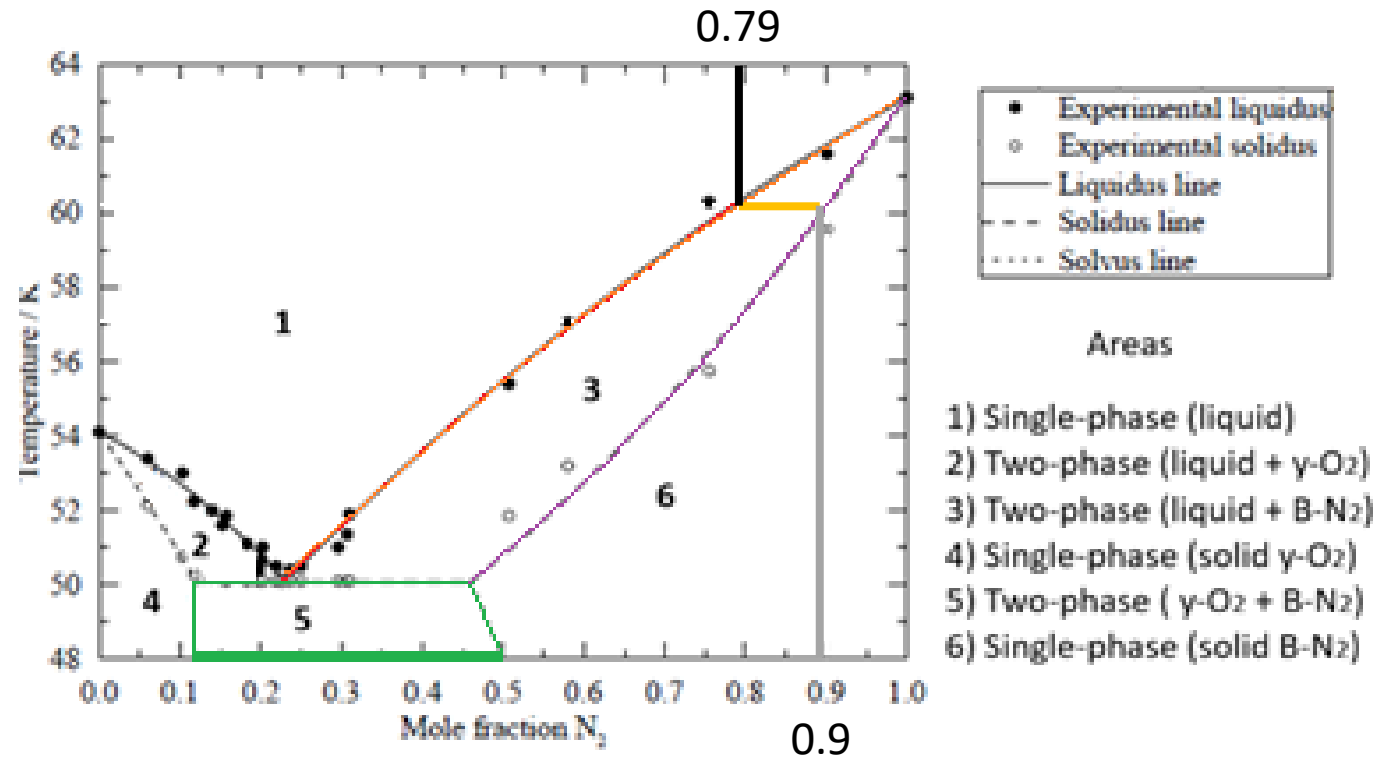


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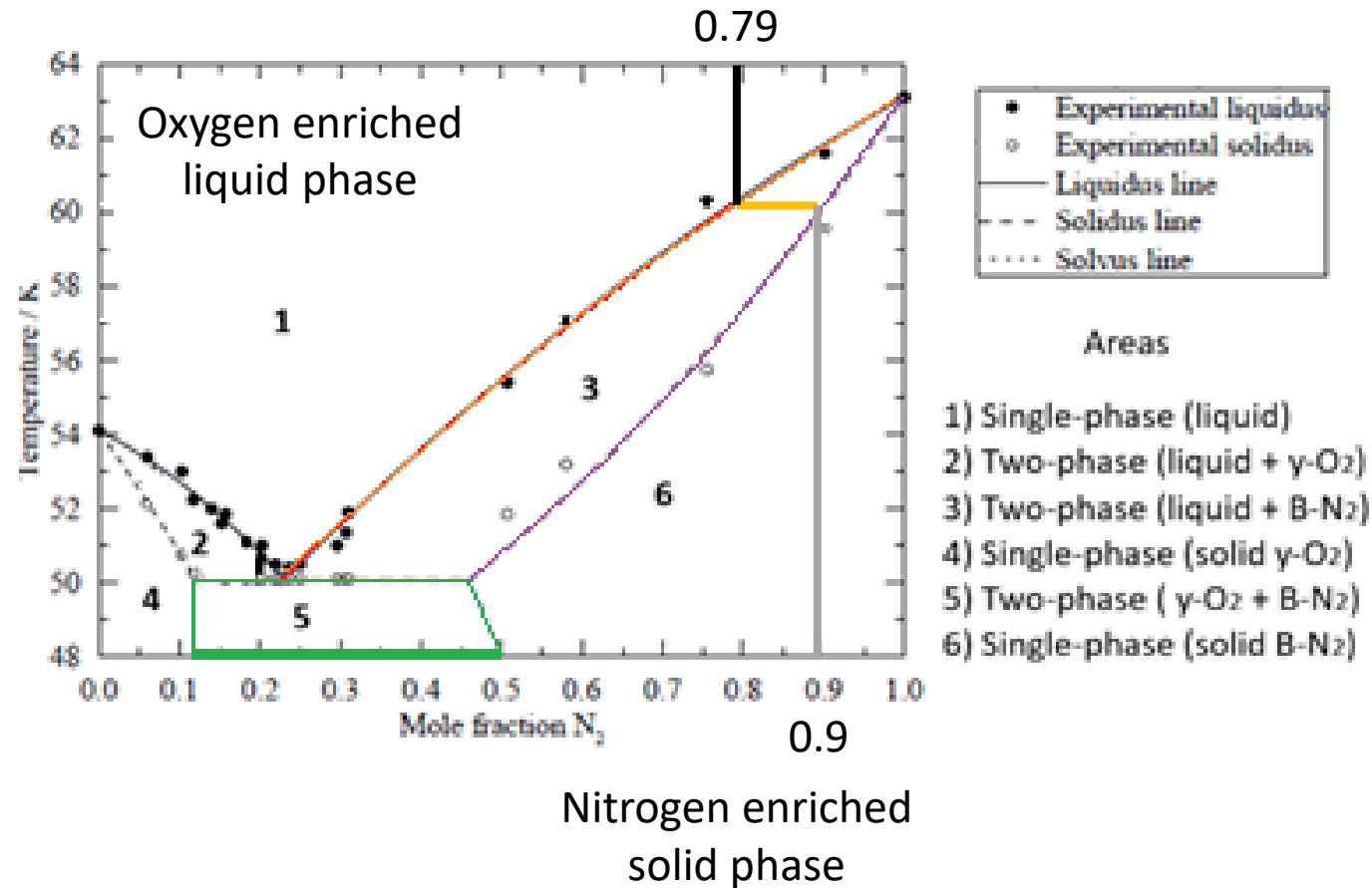
Nitrogen and Oxygen
Solid and Liquid
Binary Phase Diagram



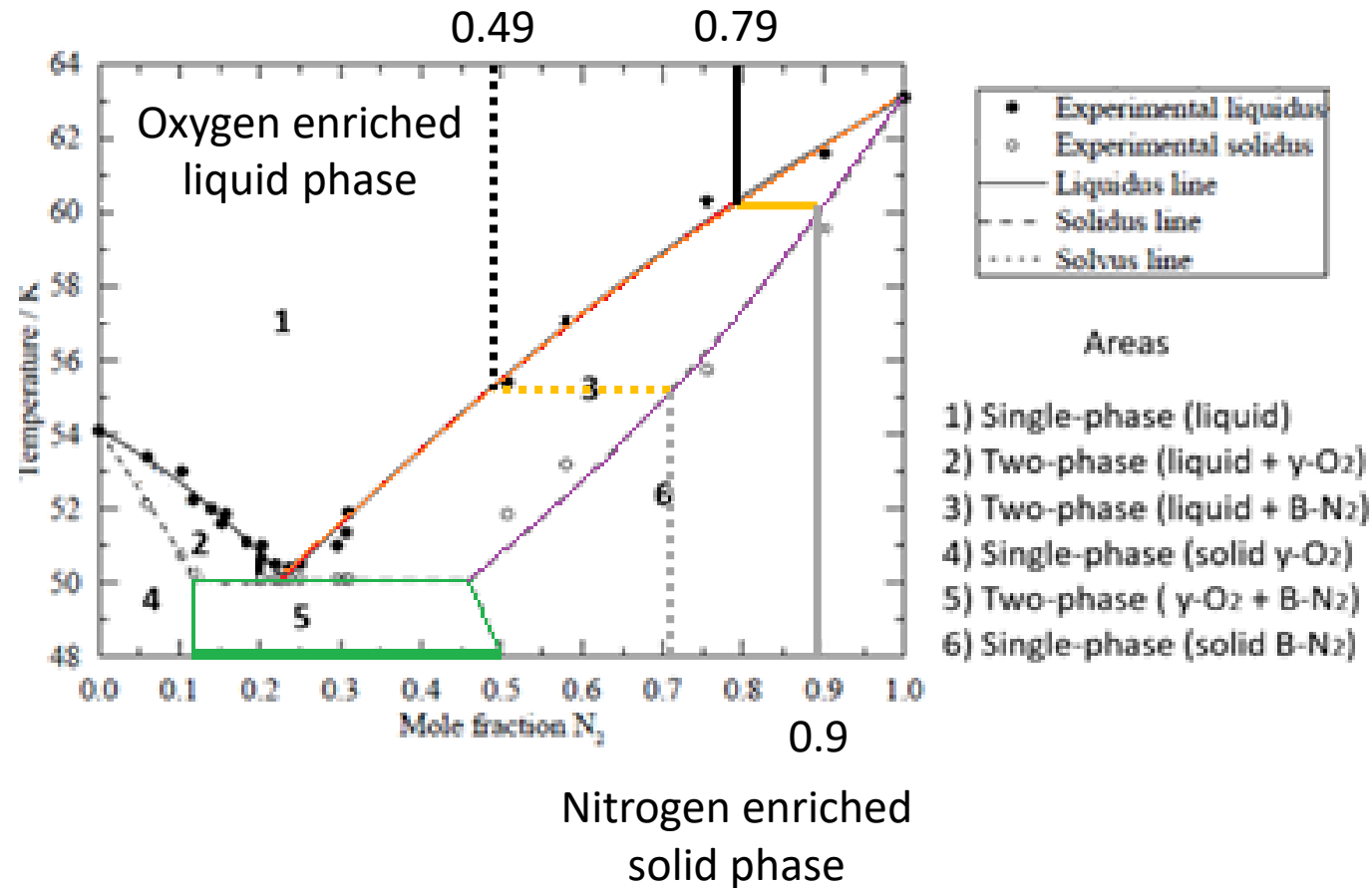
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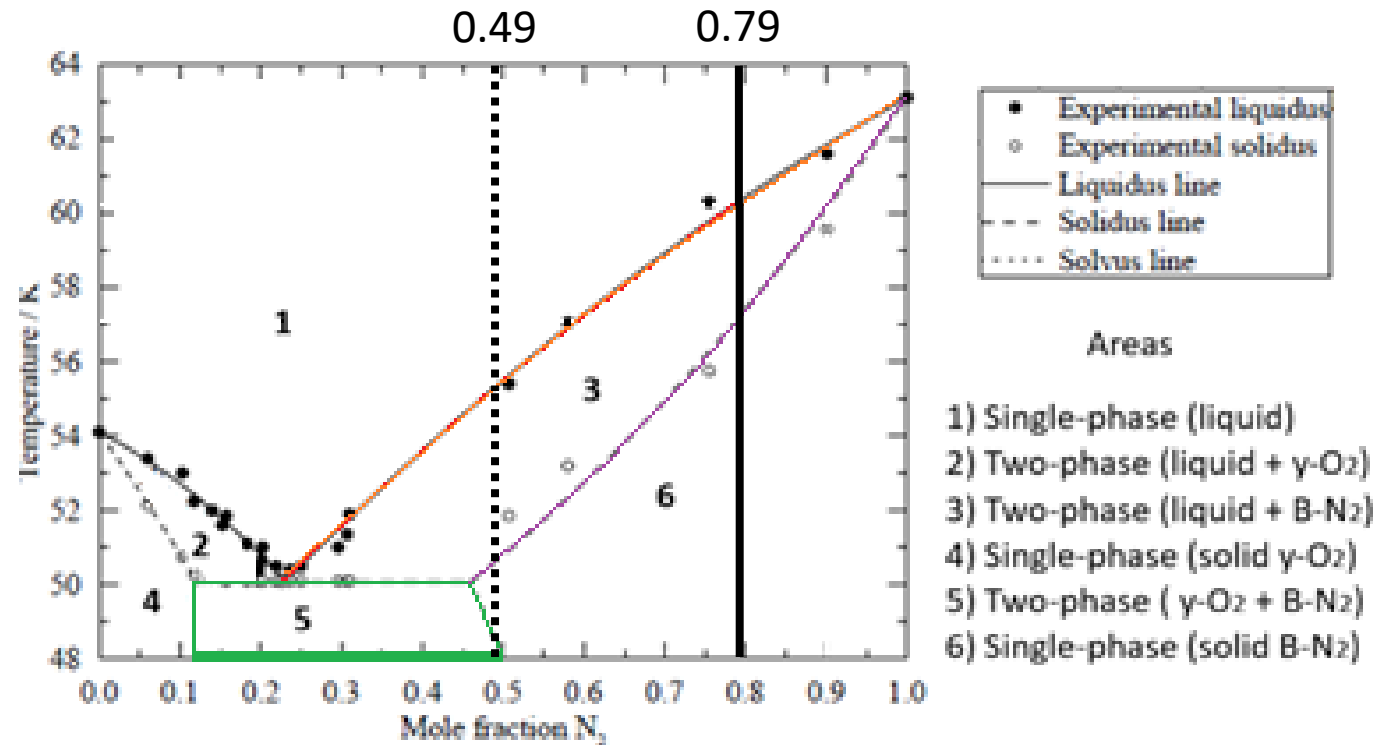
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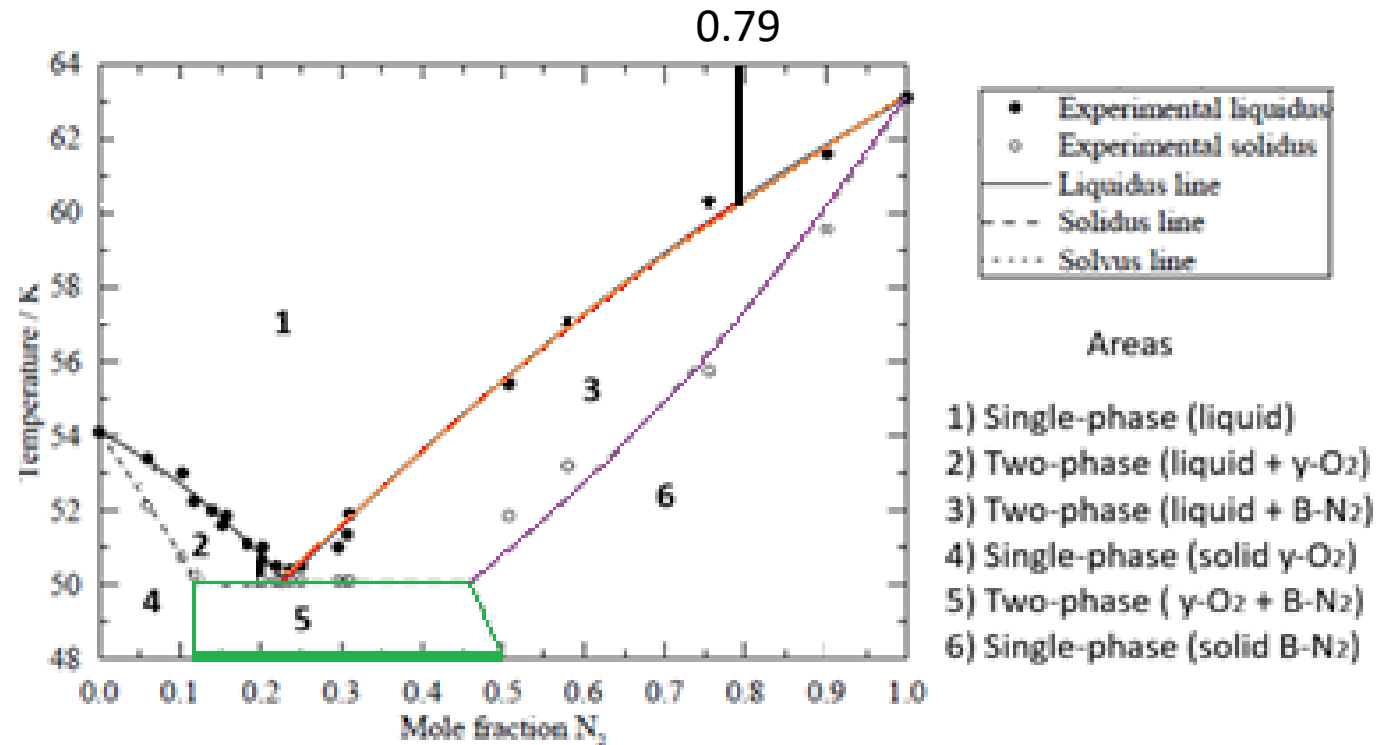


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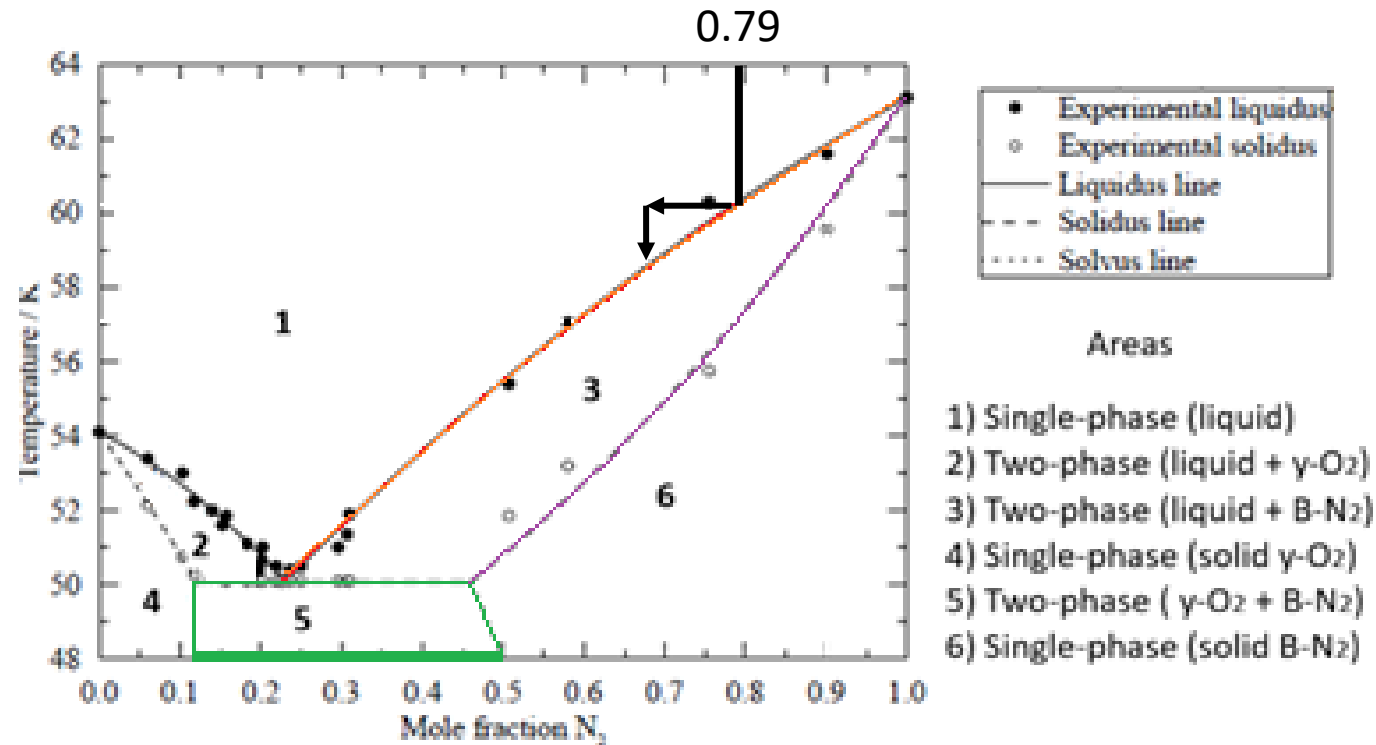
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Fractional Crystallisation



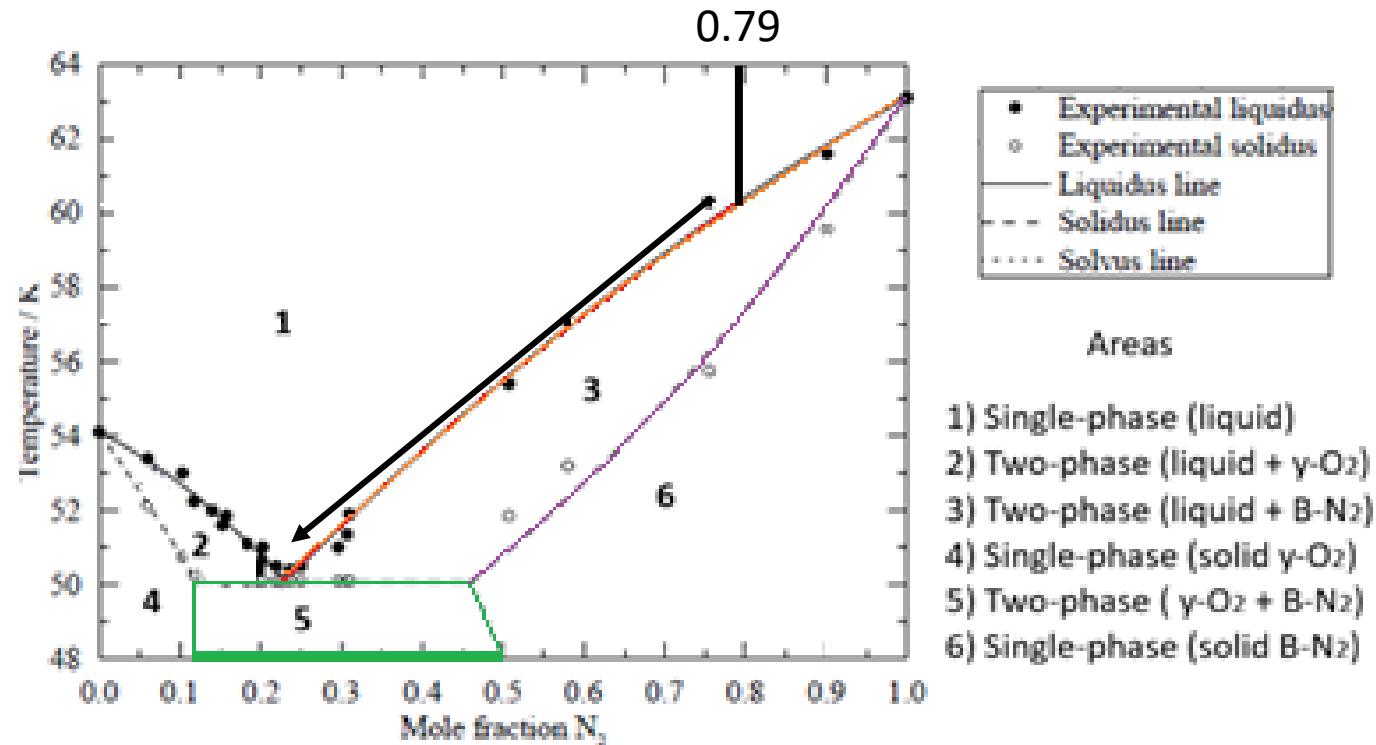
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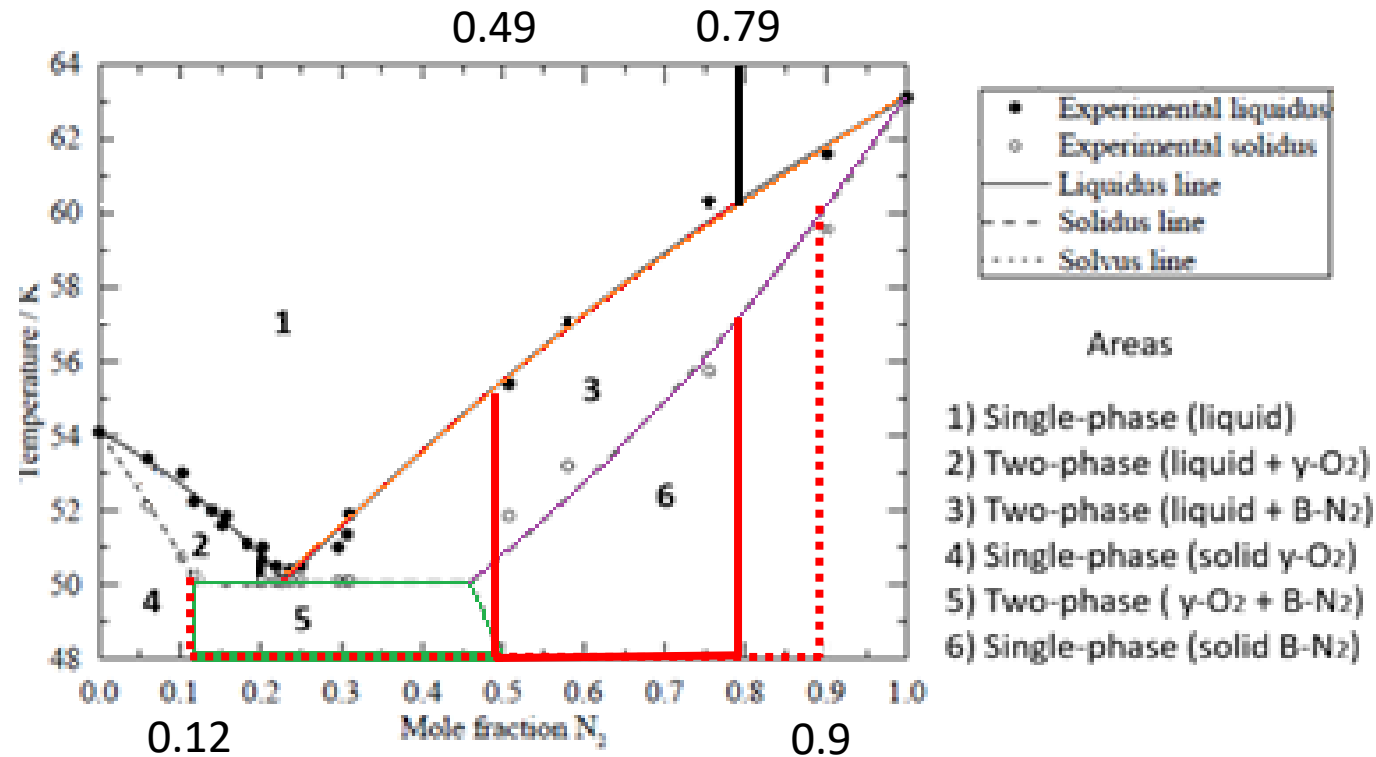
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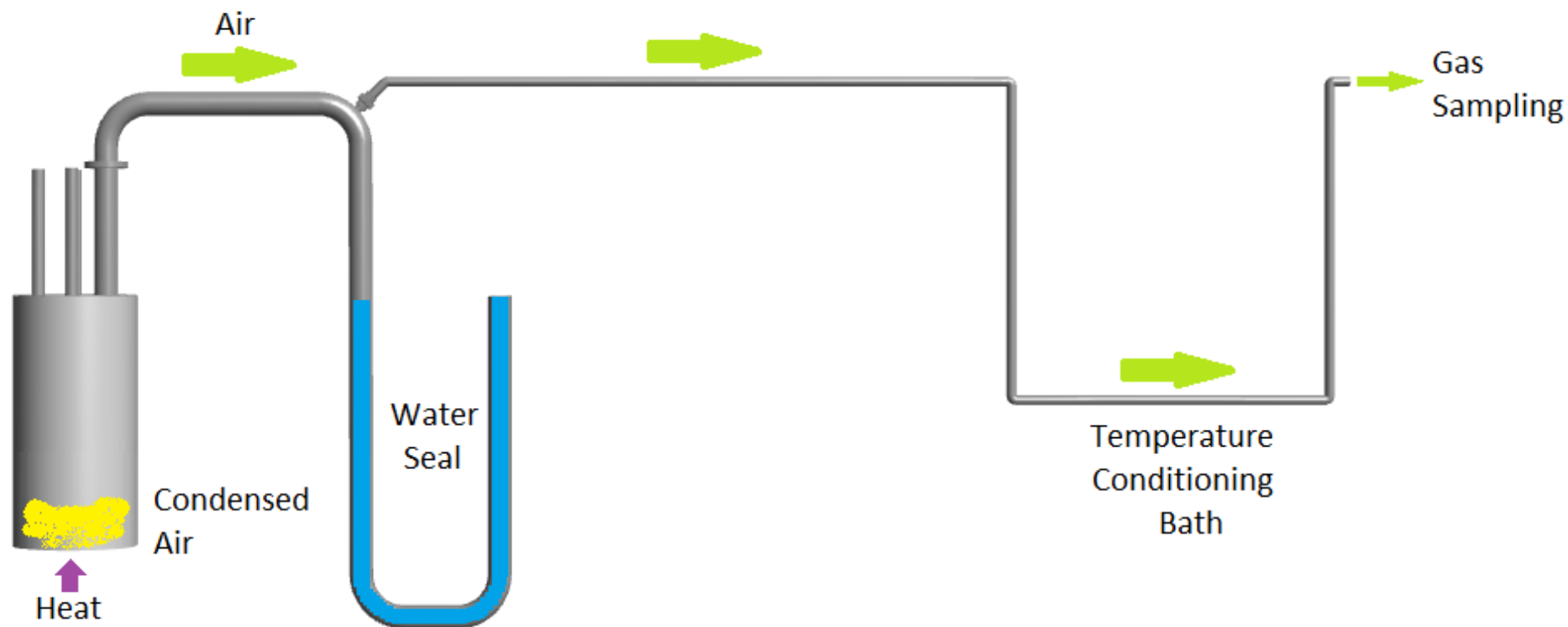


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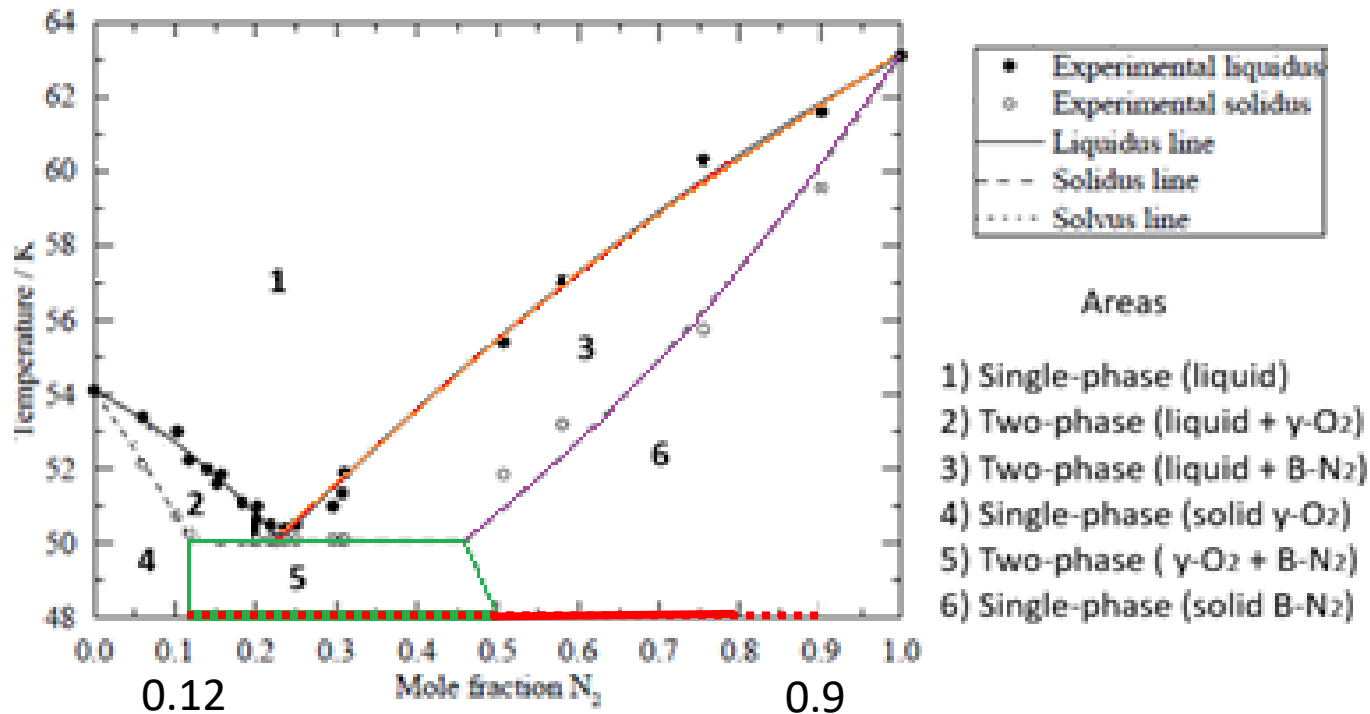
Fractional Crystallisation



Vaporisation of nitrogen and oxygen

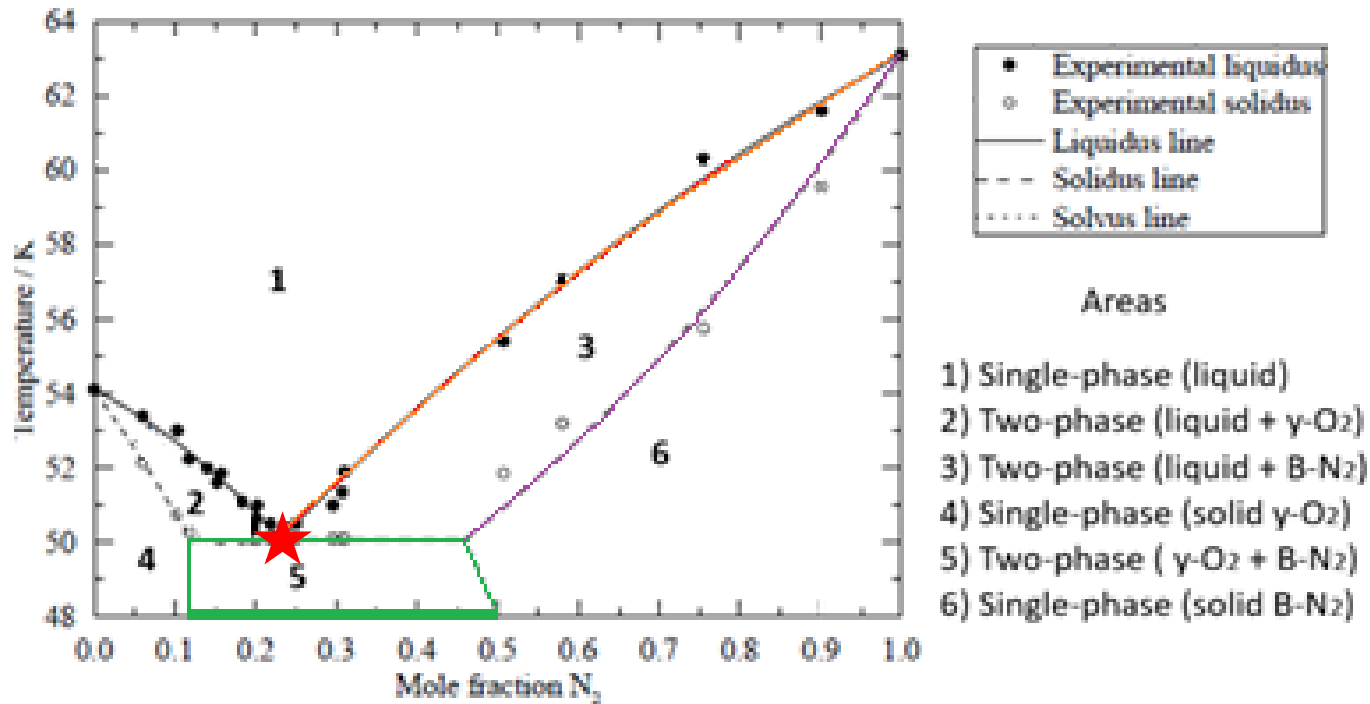


Oxygen enrichment observed during melting of oxygen and nitrogen



Oxygen enrichment observed during melting of oxygen and nitrogen

Eutectic melting



Eutectic point

51 K and 0.23 mole fraction nitrogen

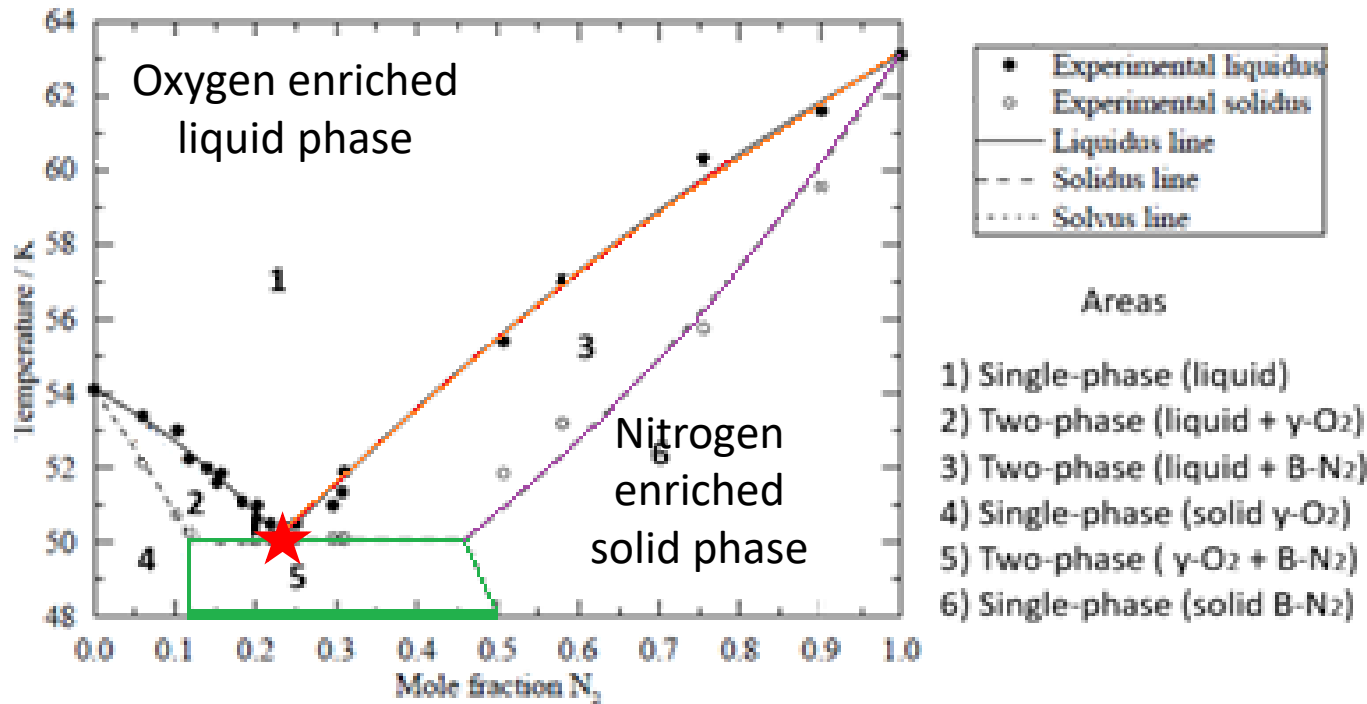
Inversion point

Kochenburger T.M., Oellrich L.R. (2015) *Evaluation of a two-stage mixed refrigerant cascade for HTS cooling below 60 K*. Phys. Procedia, 67:227–232.

Welch, J., Vizma, J. (2025) Condensed phase explosion tests from LH2 transfer systems. ELVHYS Project Report D 4.4.

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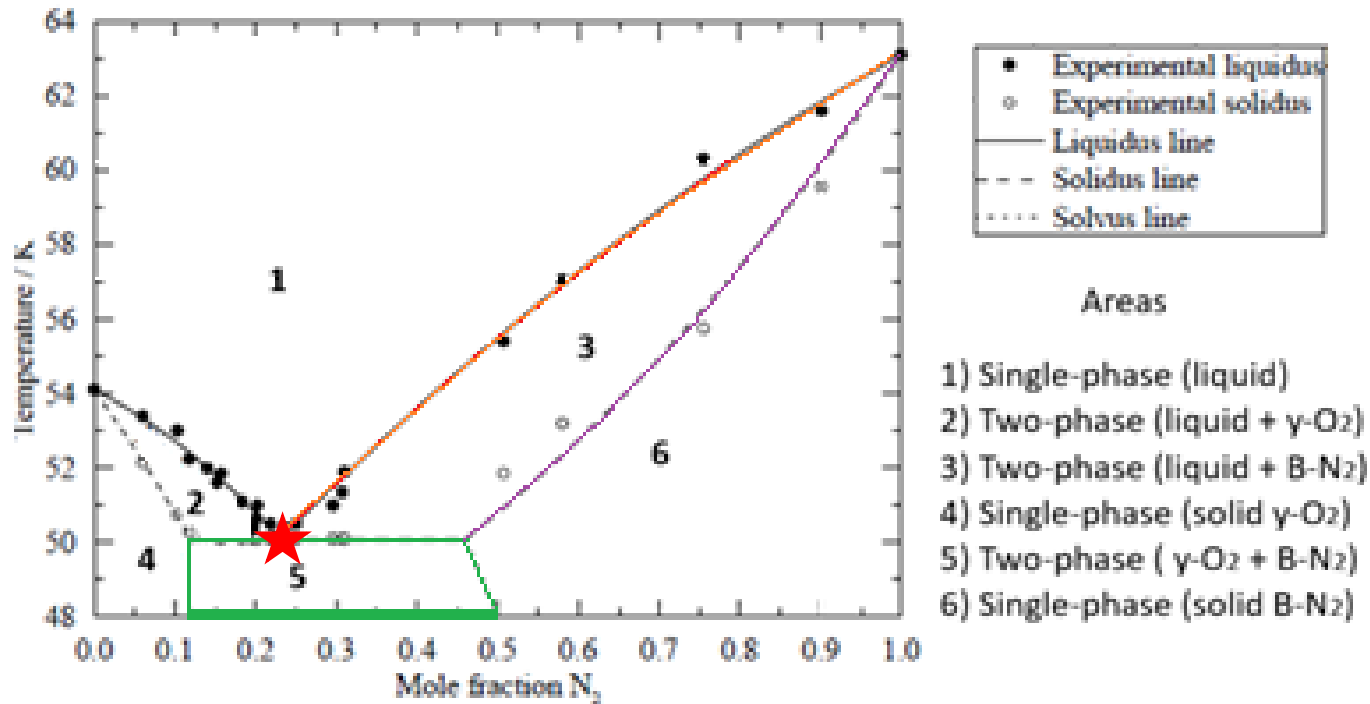
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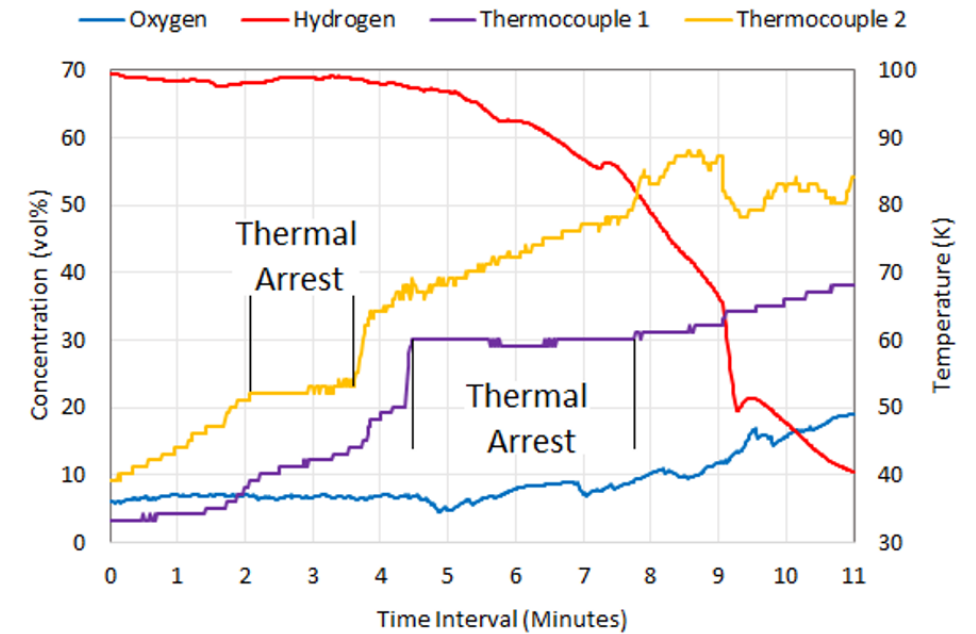
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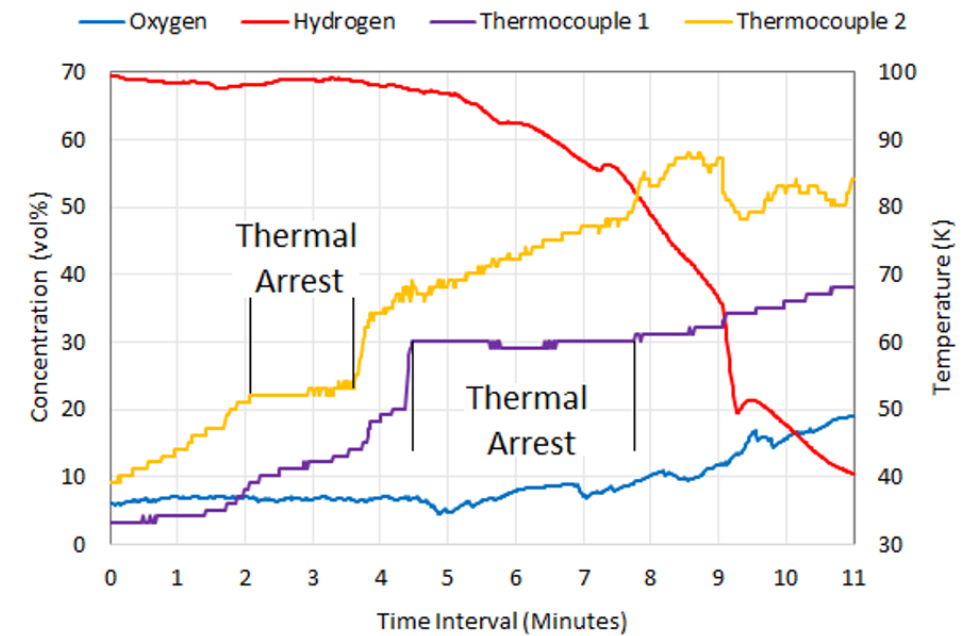
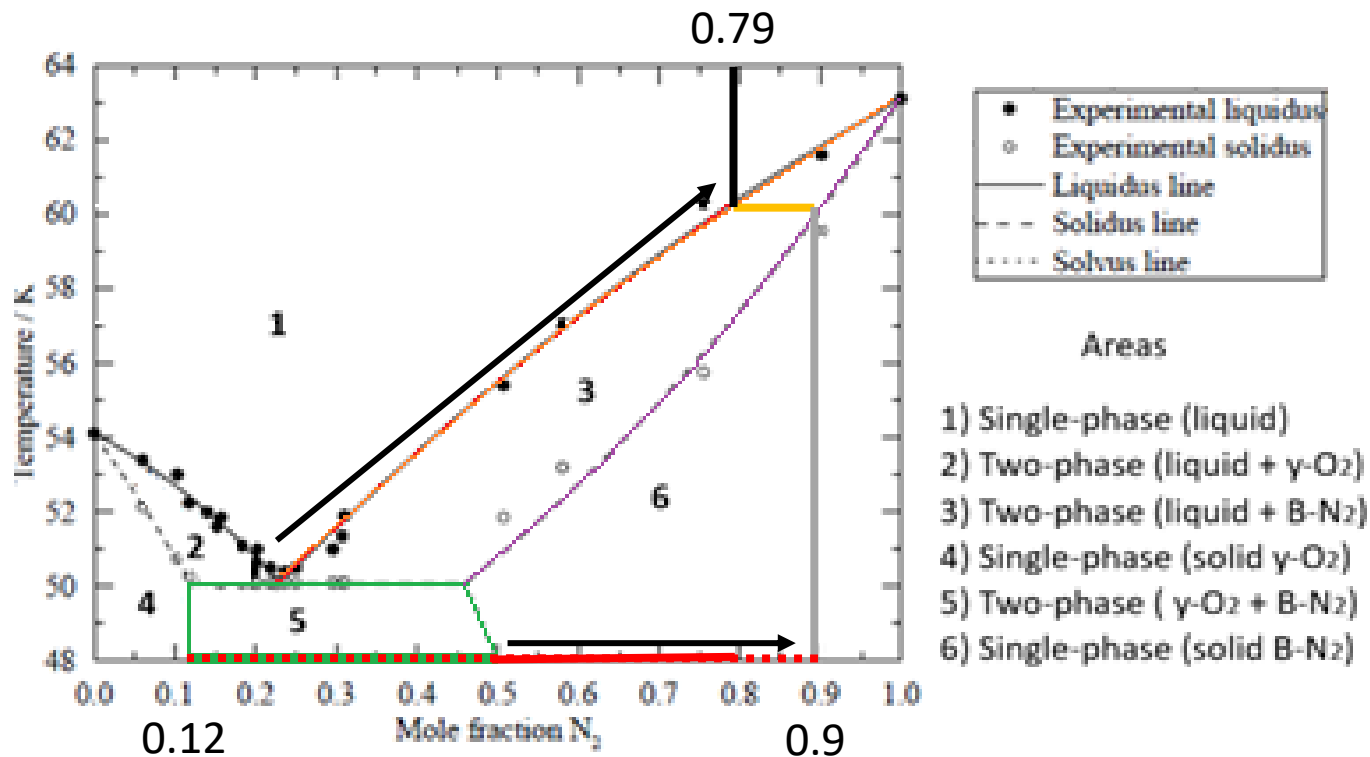
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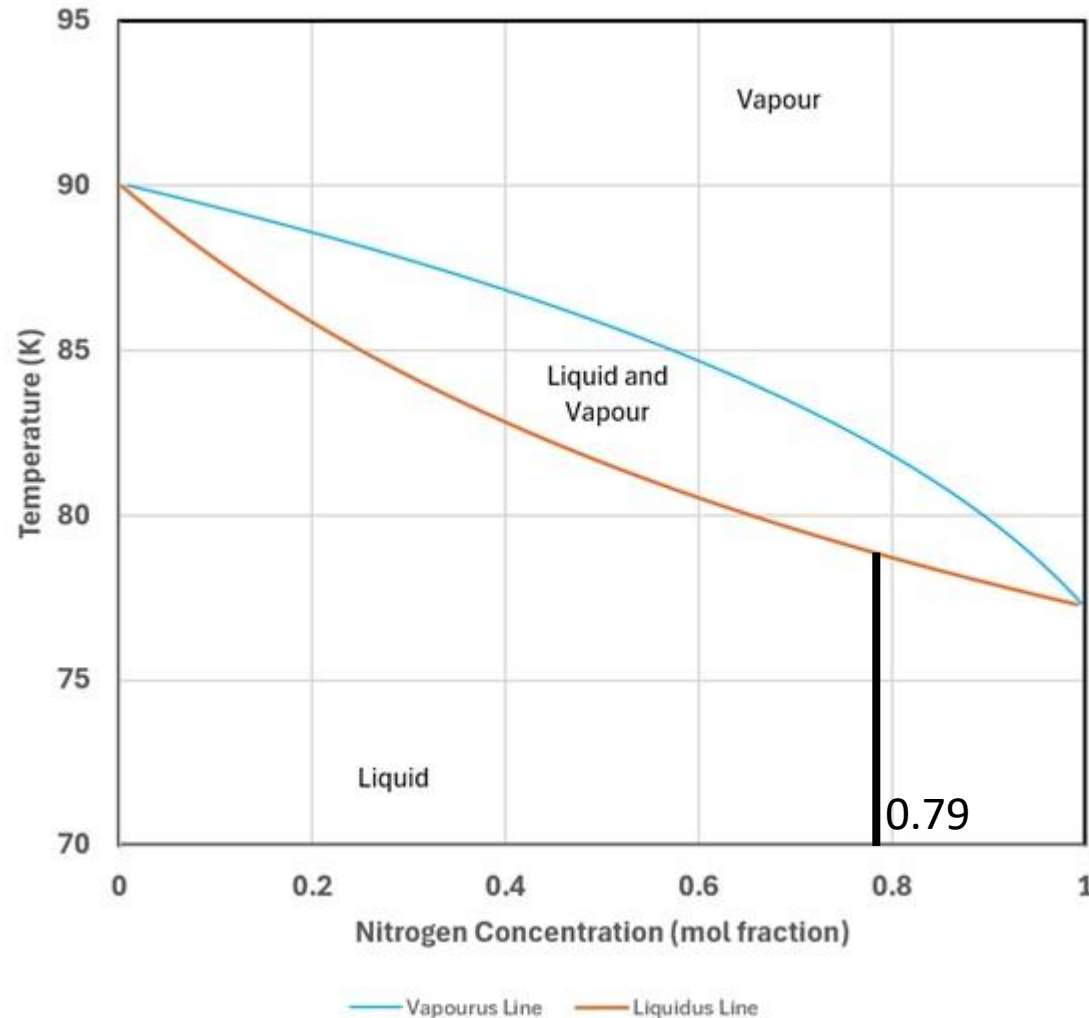
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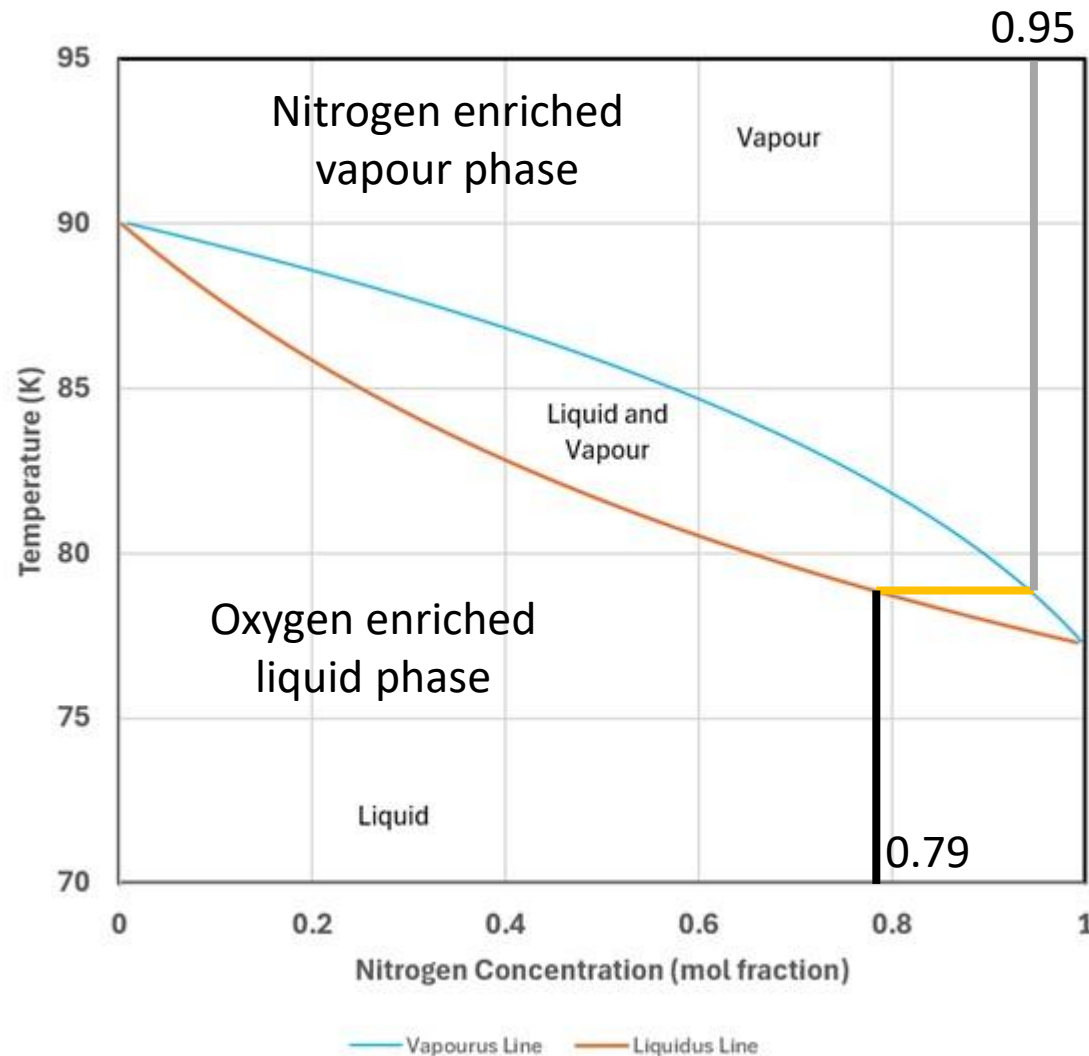
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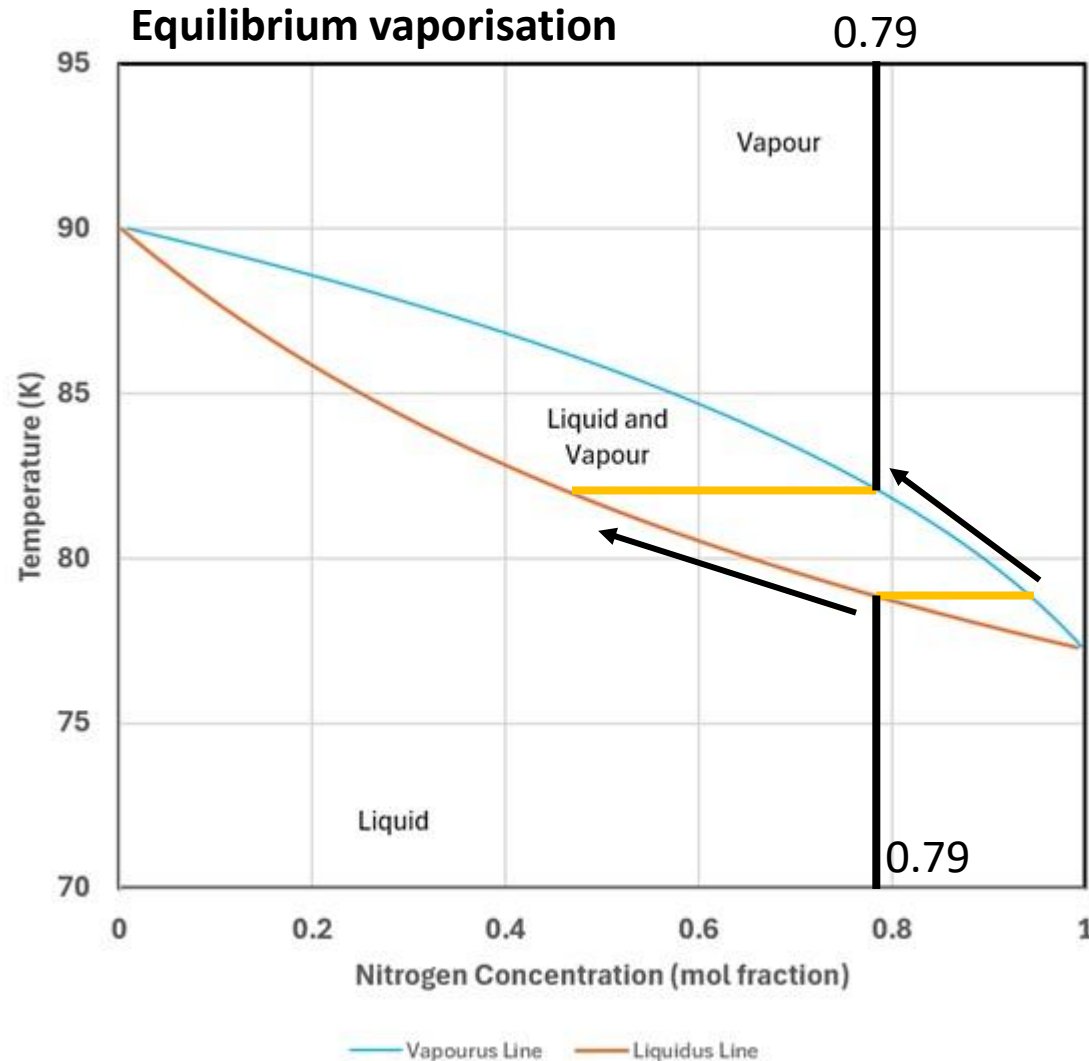
Oxygen enrichment observed during vaporisation of oxygen and nitrogen



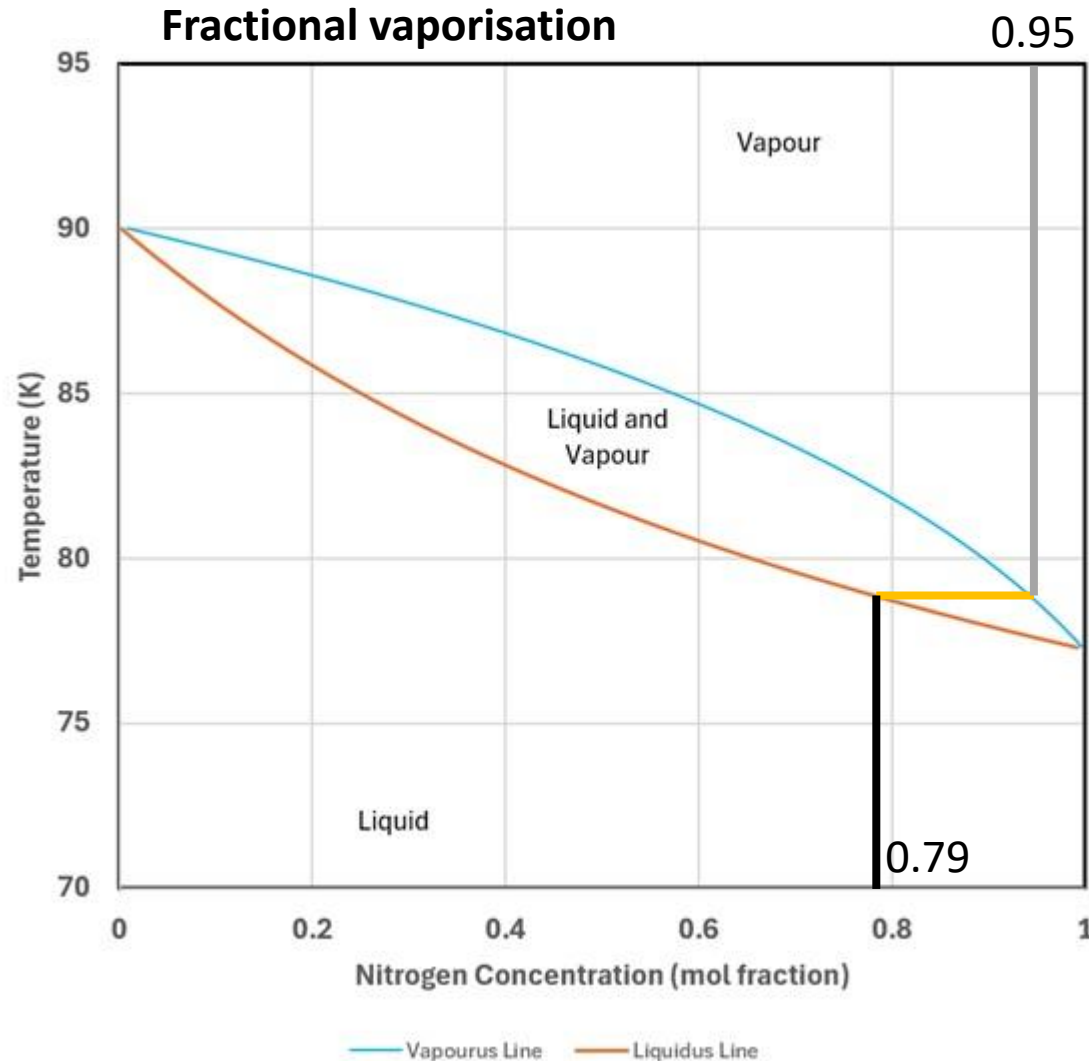
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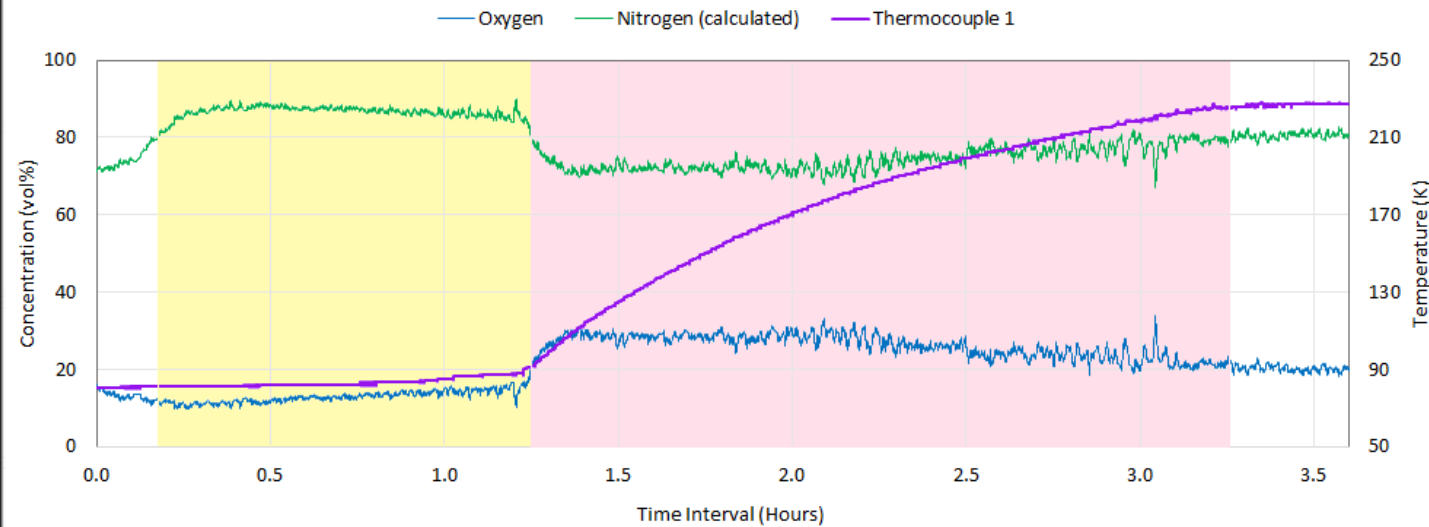
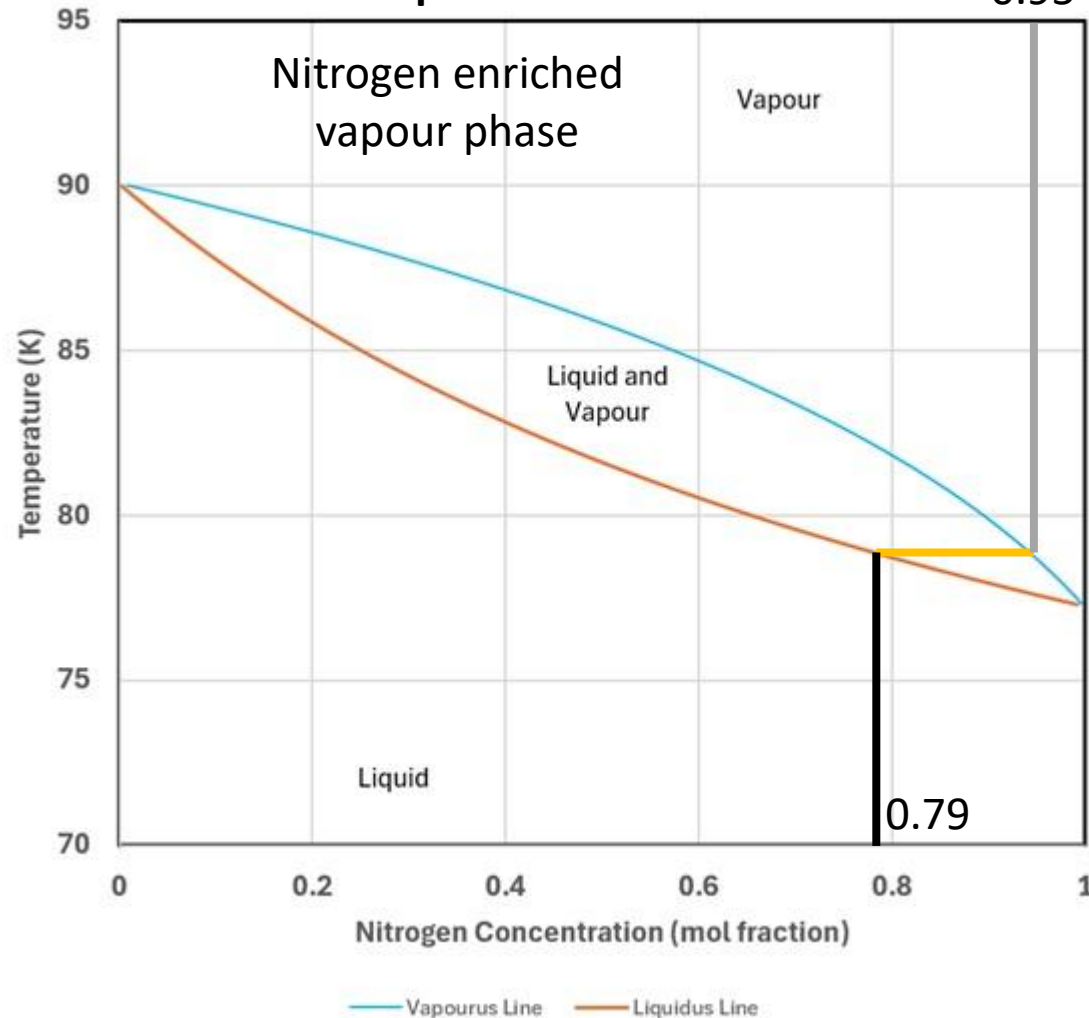
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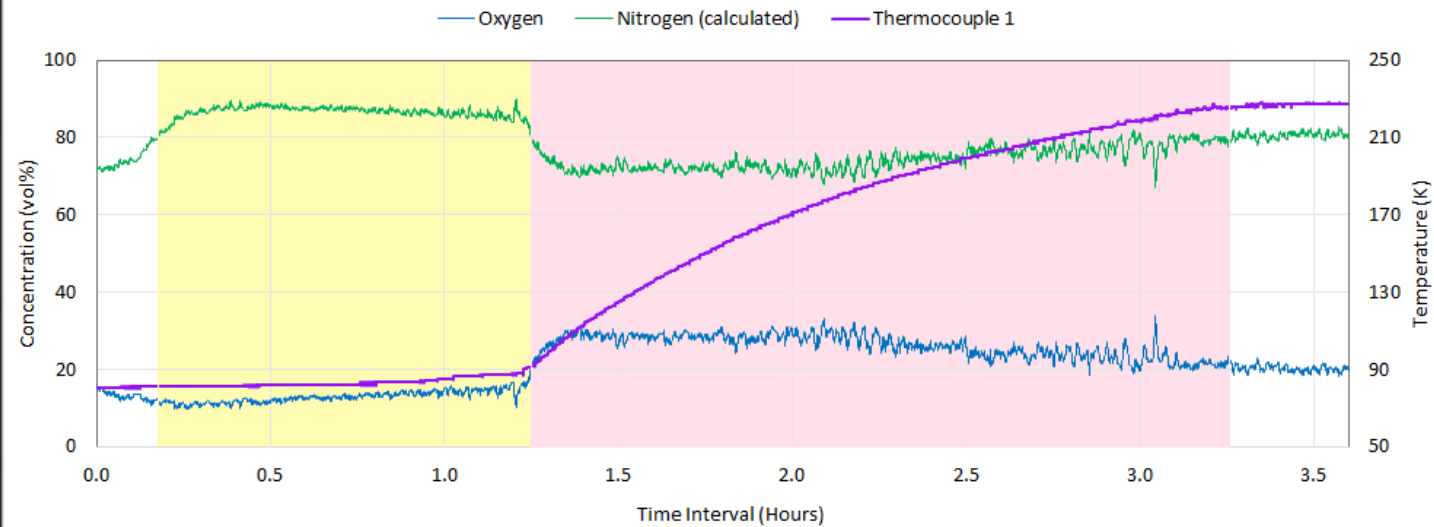
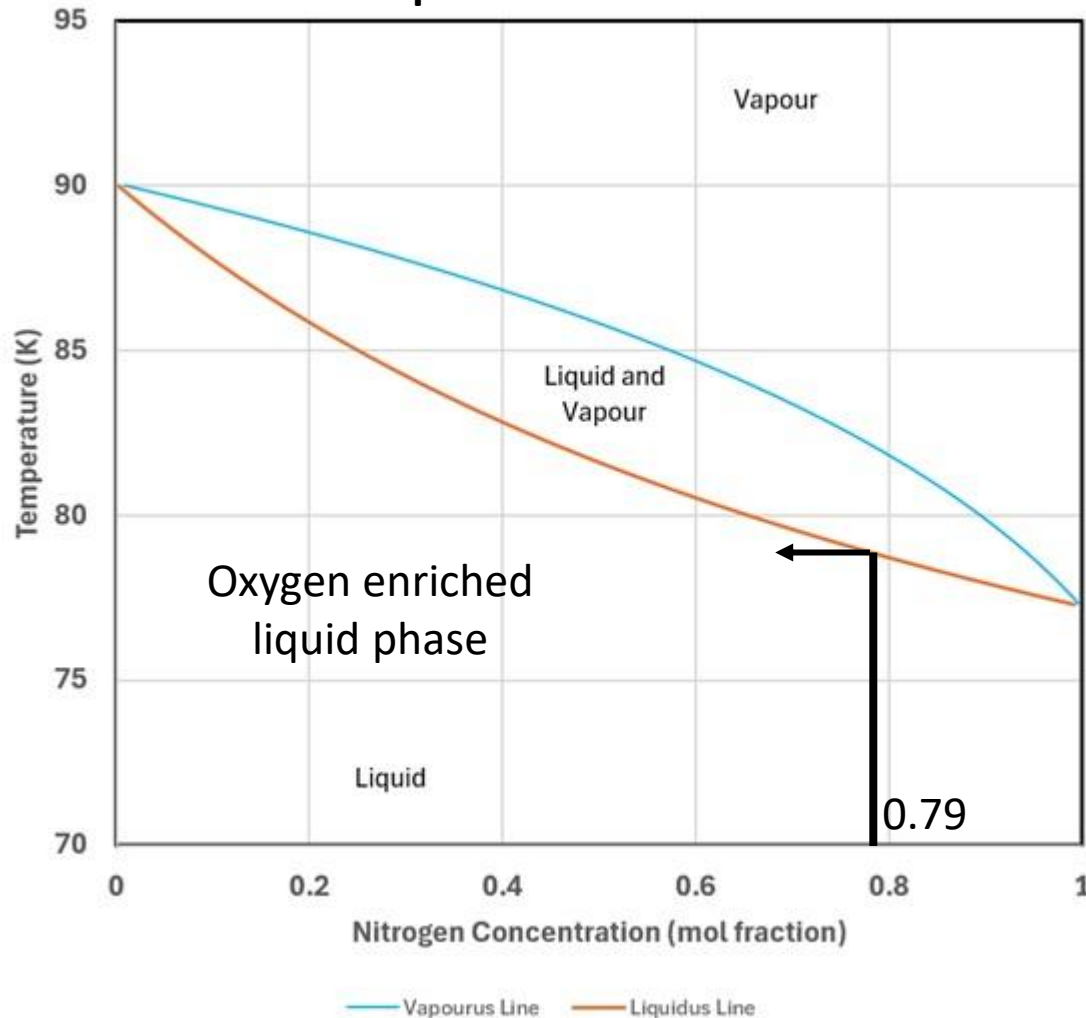
Fractional vaporisation

0.95 → Lost to atmosphere

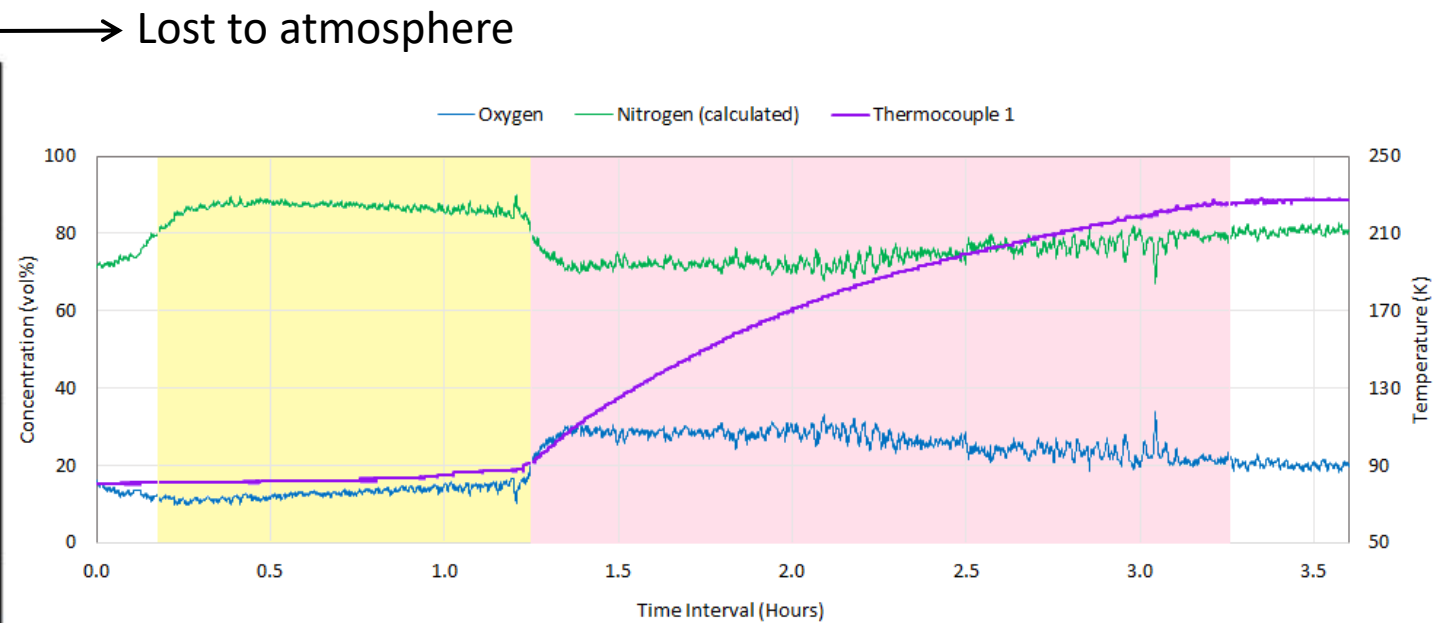
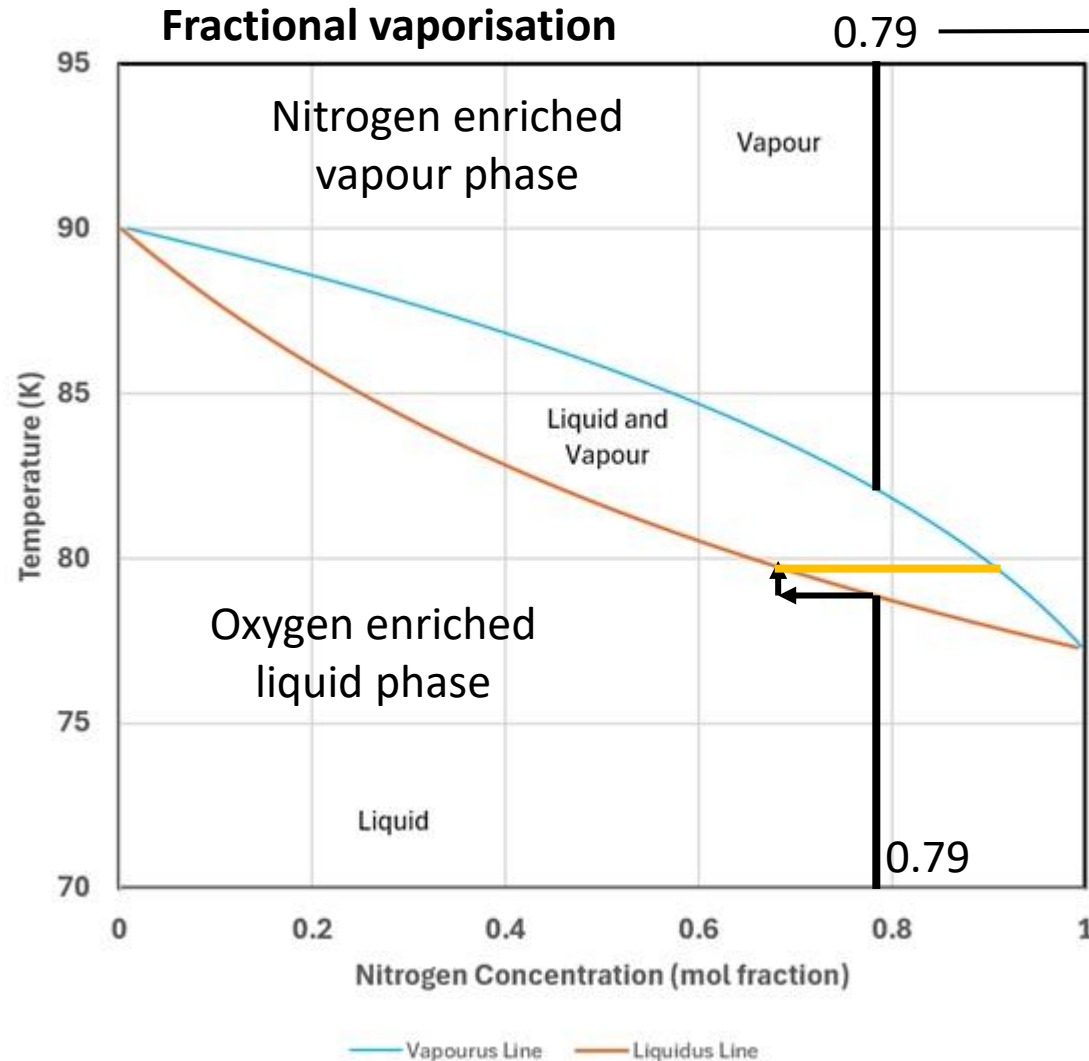


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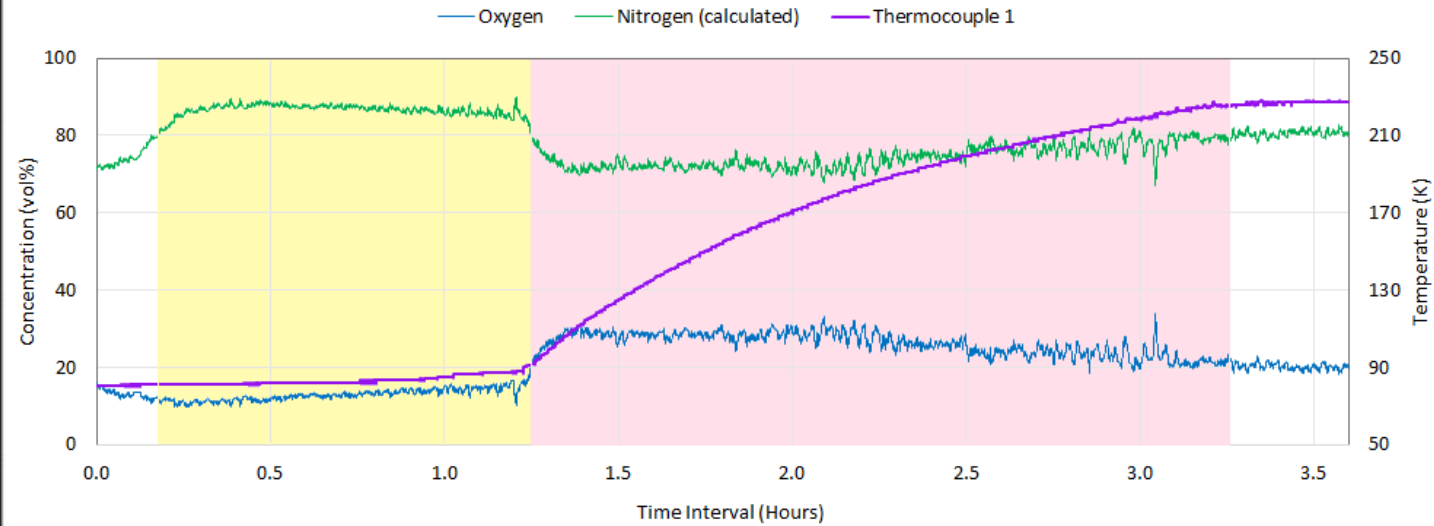
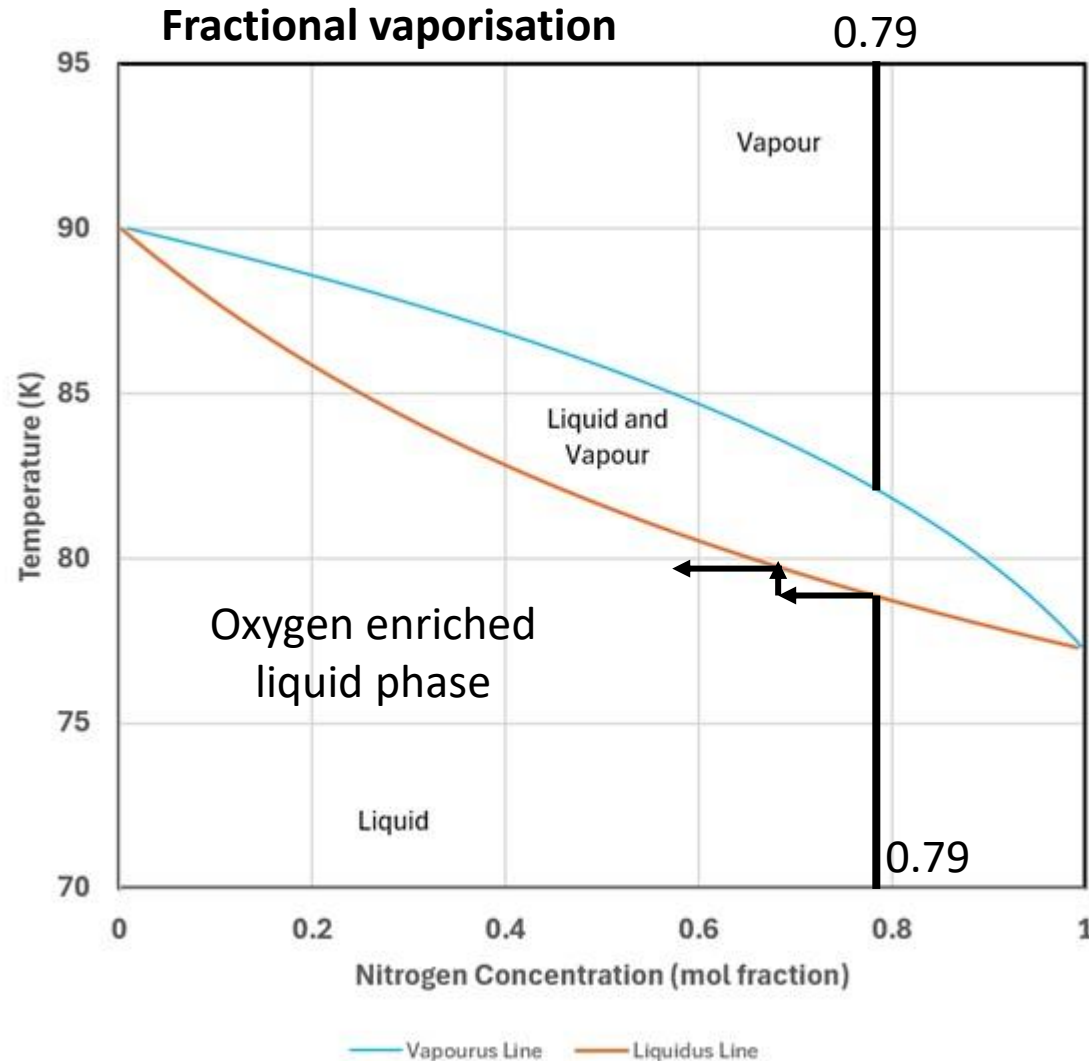
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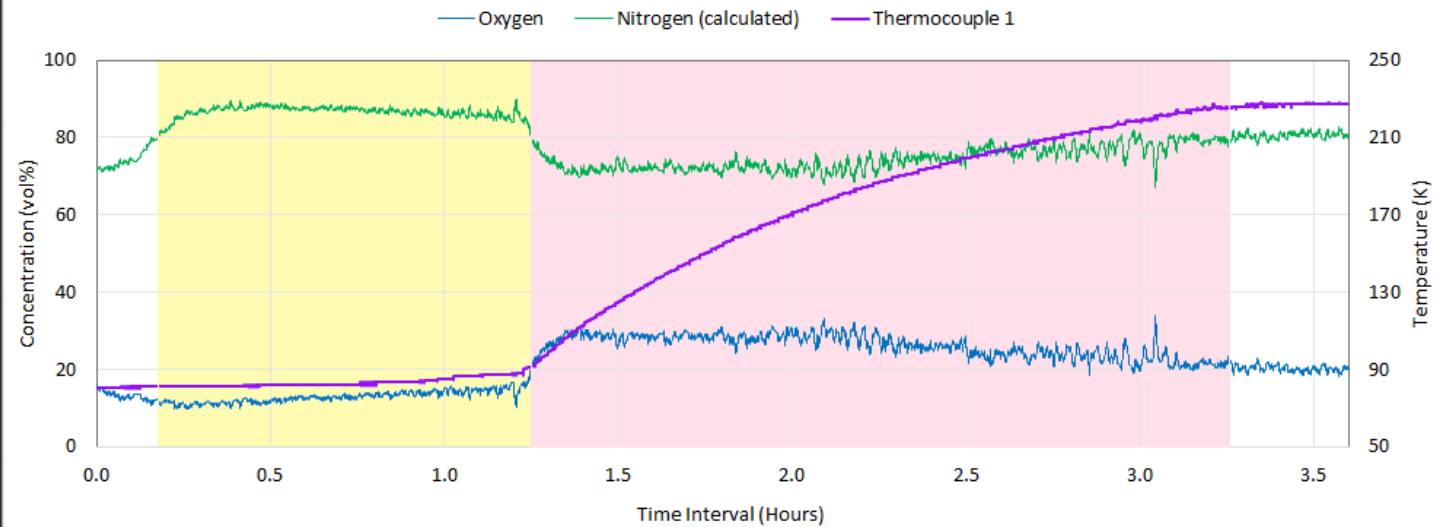
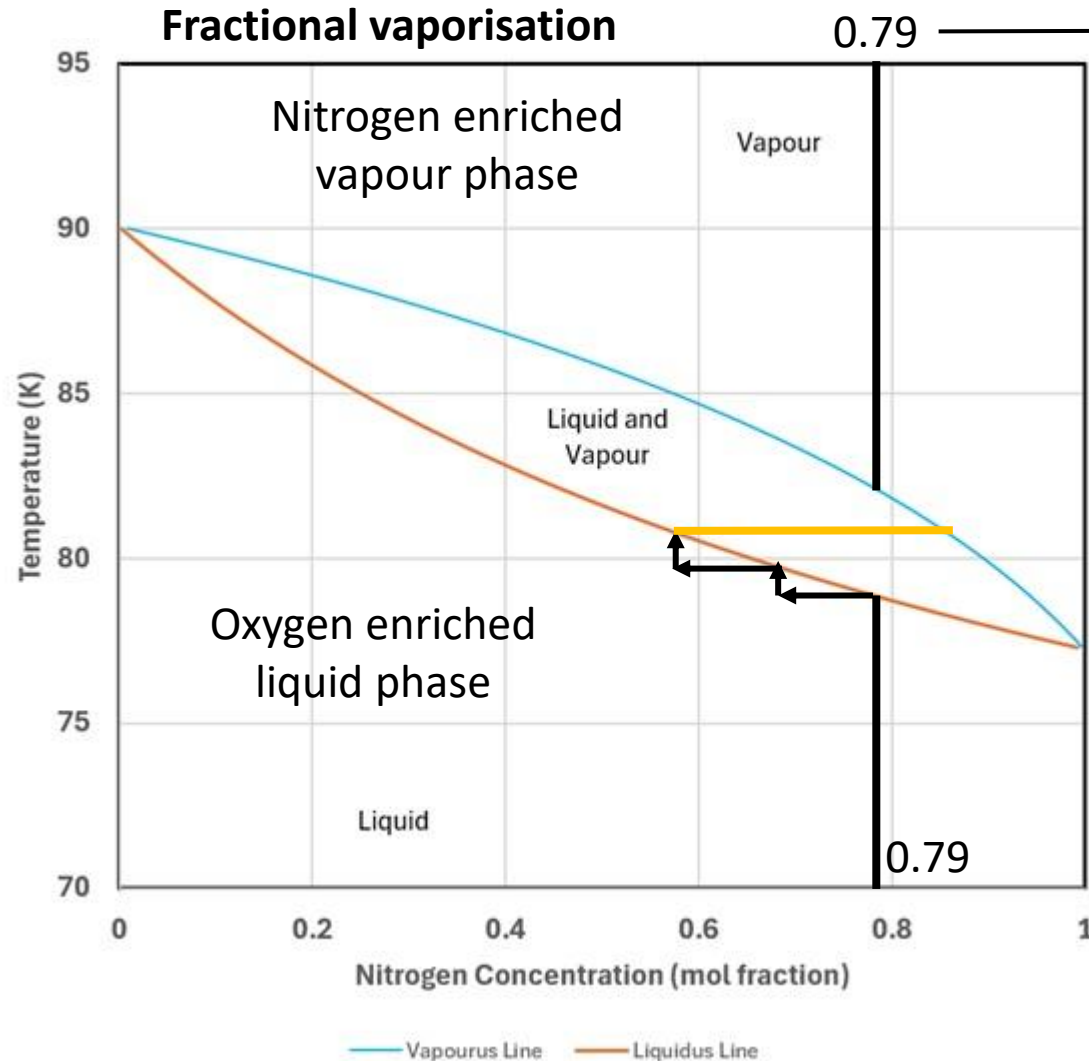
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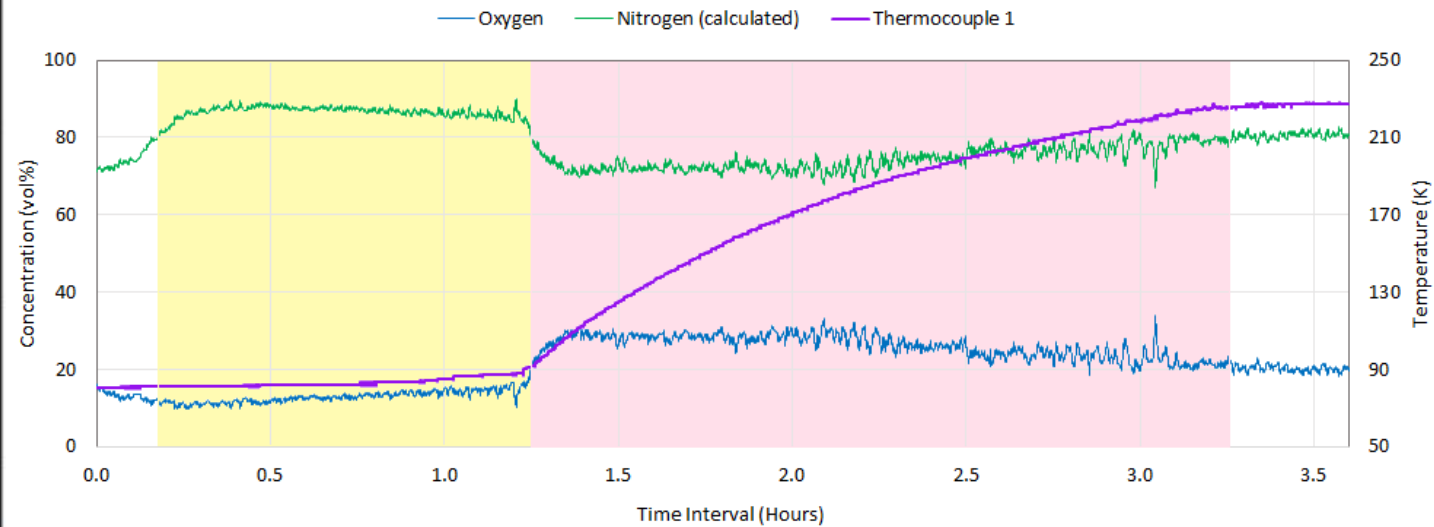
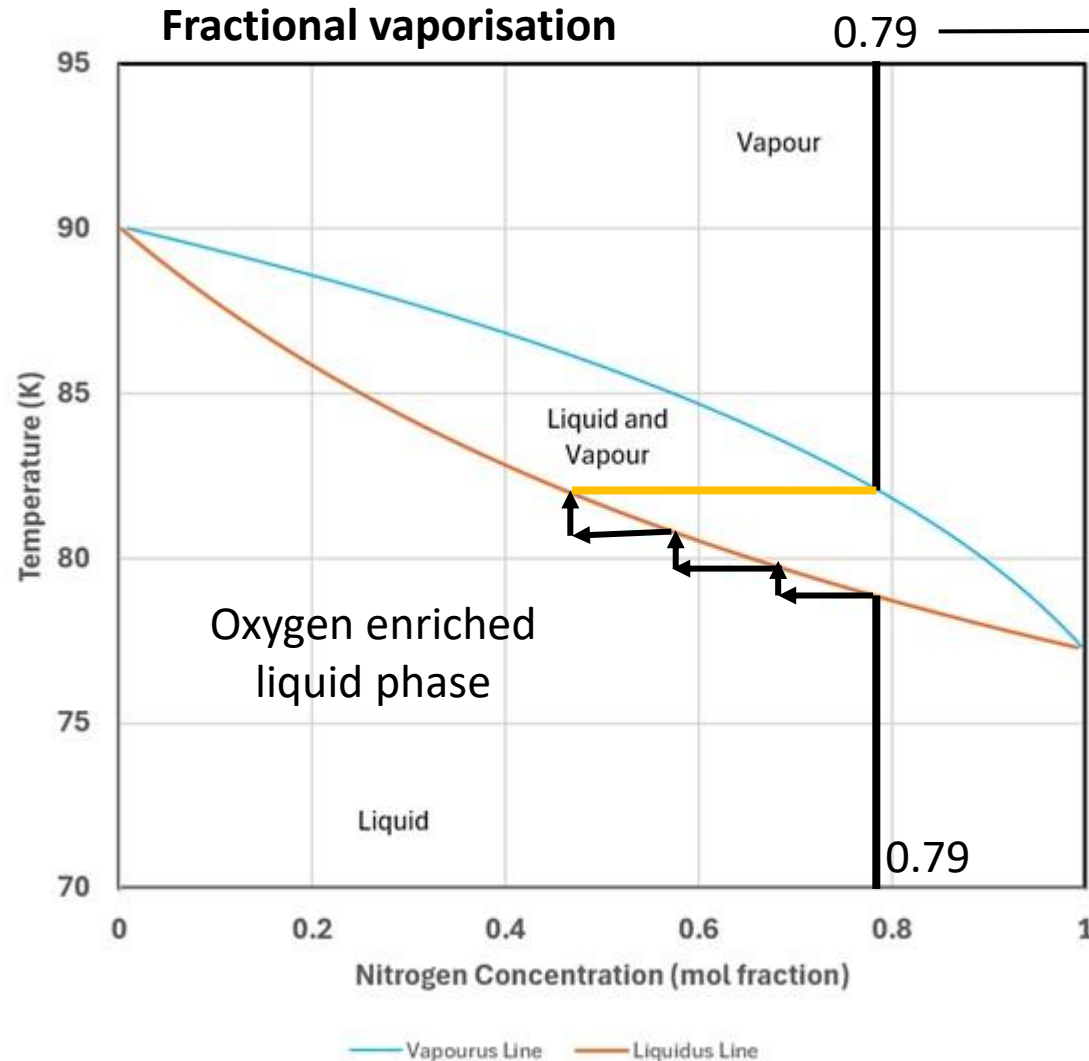
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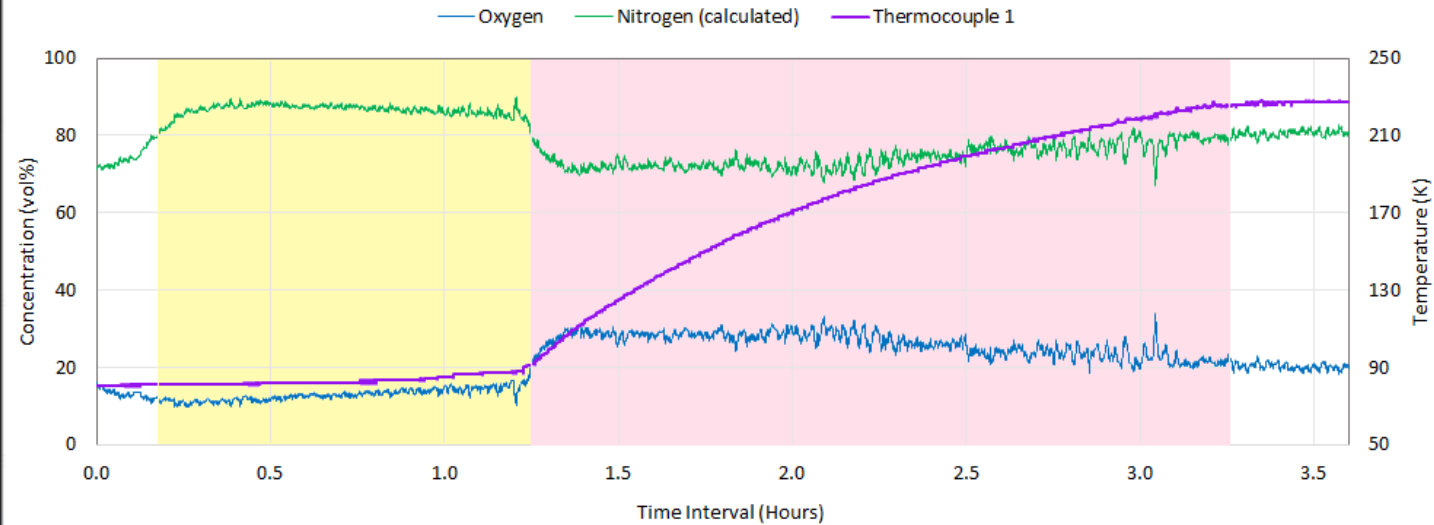
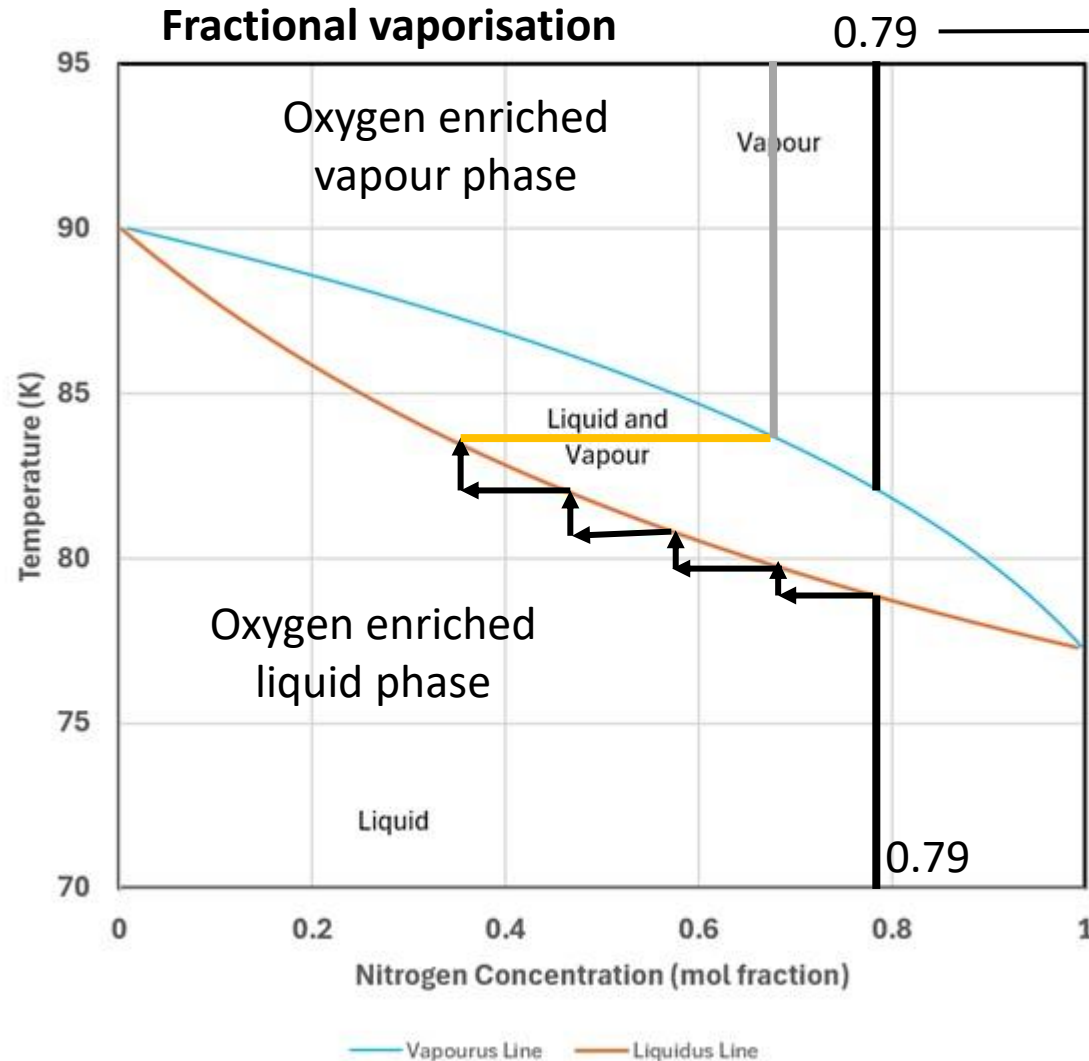
Oxygen enrichment observed during vaporisation of oxygen and nitrogen



Oxygen enrichment observed during vaporisation of oxygen and nitrogen



Oxygen enrichment observed during vaporisation of oxygen and nitrogen



Calculated oxygen enrichment in test	1	2	3
Maximum in the liquid phase (%)	119	104	103
Maximum in the vapour phase (%)	143	214	204

Conclusions

- Oxygen enrichment of the condensed phase is thermodynamically possible when air condenses into a liquid hydrogen environment.
 - This process was not observed during the ELVHYS testing, this is likely to be an artifact of the experimental set up.
- Oxygen enrichment of both the liquid and vapour phases is thermodynamically possible when a condensed nitrogen and oxygen mixture is warmed, independent of the concentration of oxygen in the condensed phase.
 - Evidence of a complicated solid to vapour phase change system for nitrogen and oxygen mixtures was observed during the ELVHYS testing.

Conclusions

- When liquid hydrogen is released from containment the surrounding air is subjected to temperatures that can lead to a nitrogen and oxygen condensed phase mixture being produced.
- When this mixture evaporates, due to the complex thermodynamics, oxygen enrichment is seen in both the liquid and vapour phase.
- However, most of the oxygen enrichment is seen after the hydrogen has vapourised.
- **Control measures, such as prevention of secondary fuel spills and control of ignition sources, should adequately manage this risk.**

Acknowledgements

The following people were instrumental in the completion of this work:

- Research team: Wayne Rattigan, Janni Vizma, and Greg Wray
- Photography and videos: Alex Grimes, Josh Moran, Trystan Lang, and Keith Tremble
- The entire HSE Buxton workshop team, but especially Martin Johnson and Stuart Buckingham.



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Thank you for your attention

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