CSIRO's Metal Membrane Technology (MMT) – *Technical Update*

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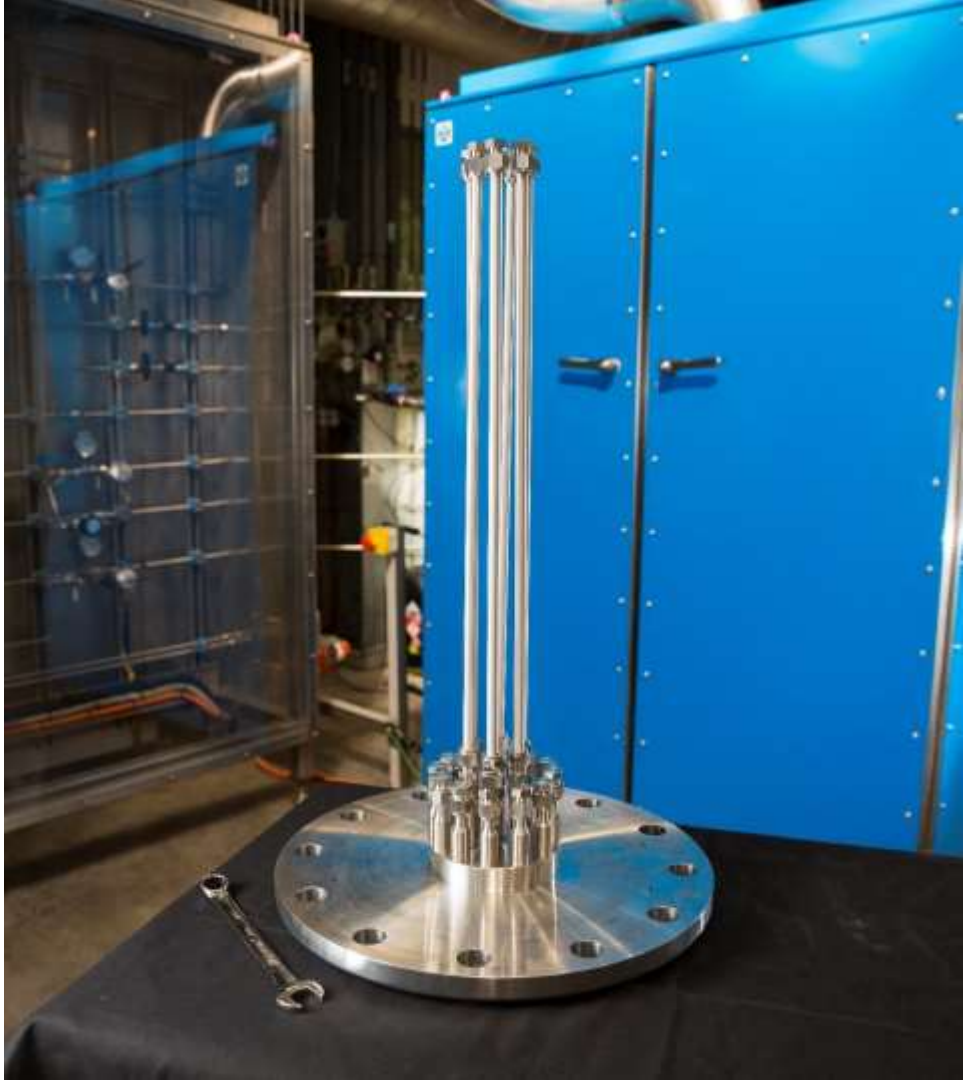

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CSIRO – MMT technical update

- Background to the technology and 2018 demonstration
- Scaling up of manufacturing since then
- Preserving H_2 product purity, using latest seal technology
- 40 kg/day scale pilot – 2022
- 200 kg/day scale pilot – current focus

Fortescue – MMT commercial update

Ammonia as a hydrogen carrier

Building on existing industries and infrastructure

Reducing cost of electrolysis

New renewable energy export industry

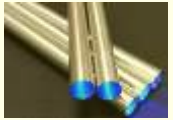
Scalable NH_3 production

Decarbonisation of heavy transport and distributed power
Engines, fuel cells, turbines…

Solar thermal

H_2

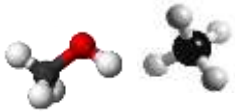
NH_3



H_2

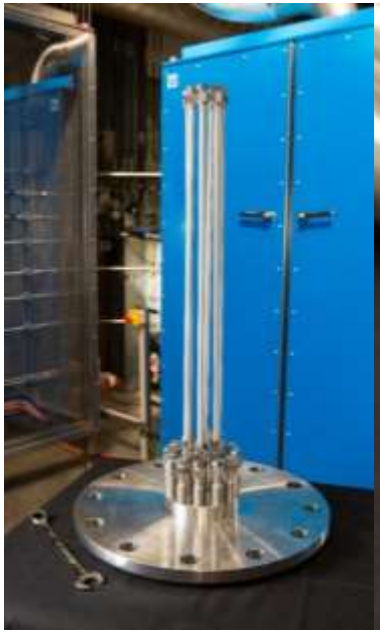
Ammonia cracking for decarbonisation of vehicle transport systems

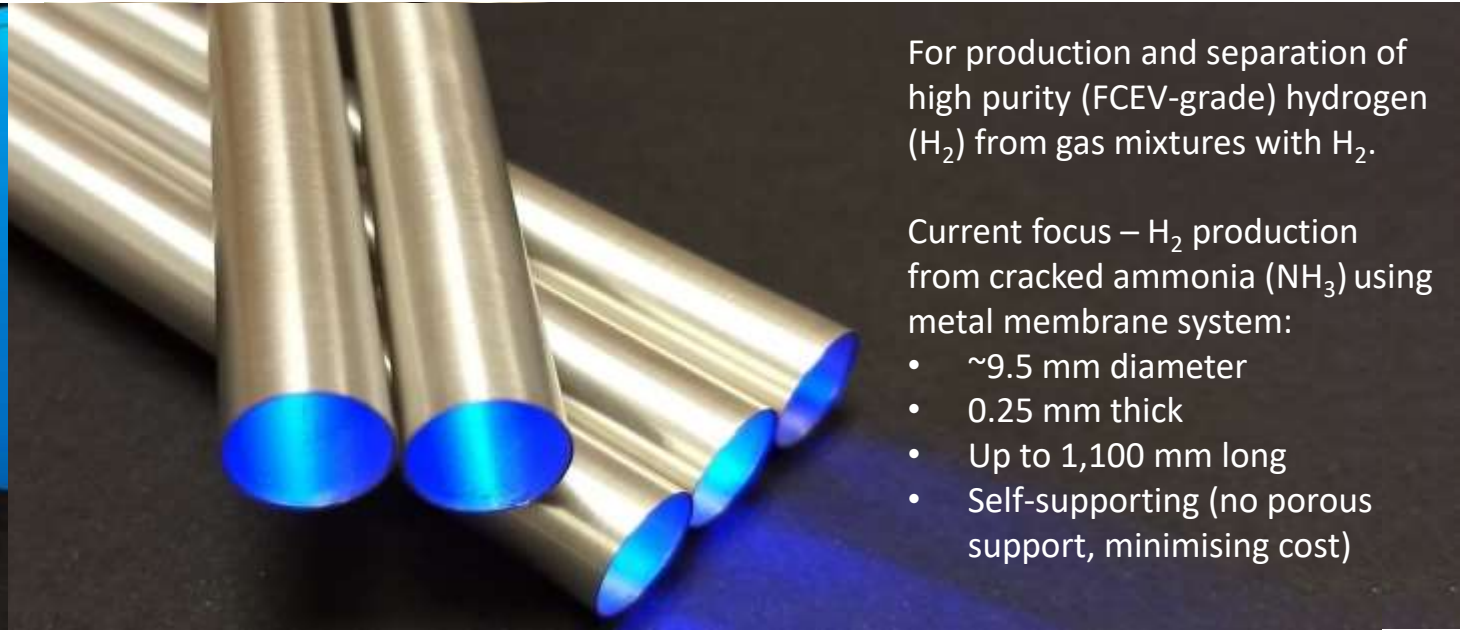
Gasification routes for coal, biomass & wastes to hydrogen



Other carriers:
methanol, SNG…

CSIRO's Metal Membrane Technology (MMT)





For production and separation of high purity (FCEV-grade) hydrogen (H_2) from gas mixtures with H_2.

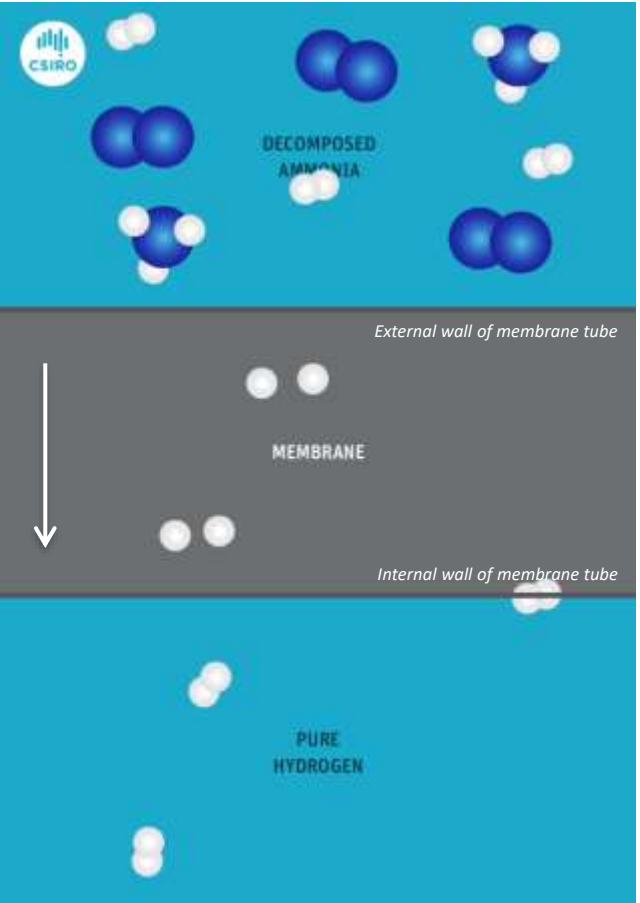
Current focus – H_2 production from cracked ammonia (NH_3) using metal membrane system:

- ~9.5 mm diameter
- 0.25 mm thick
- Up to 1,100 mm long
- Self-supporting (no porous support, minimising cost)

NH_3-to-H_2 System Demonstrations

- **5 kg/day** proof-of-concept scale – demonstrated in Brisbane, 2018
- **40 kg/day** pilot scale – completed 2022
- **200 kg/day** pilot demonstration scale up – current focus, UK 2023-24

Vanadium-based membranes for H_2 purification



High pressure +
Mixed Gas Stream
(NH_3, N_2, H_2)

Feed-side catalyst (Pd)

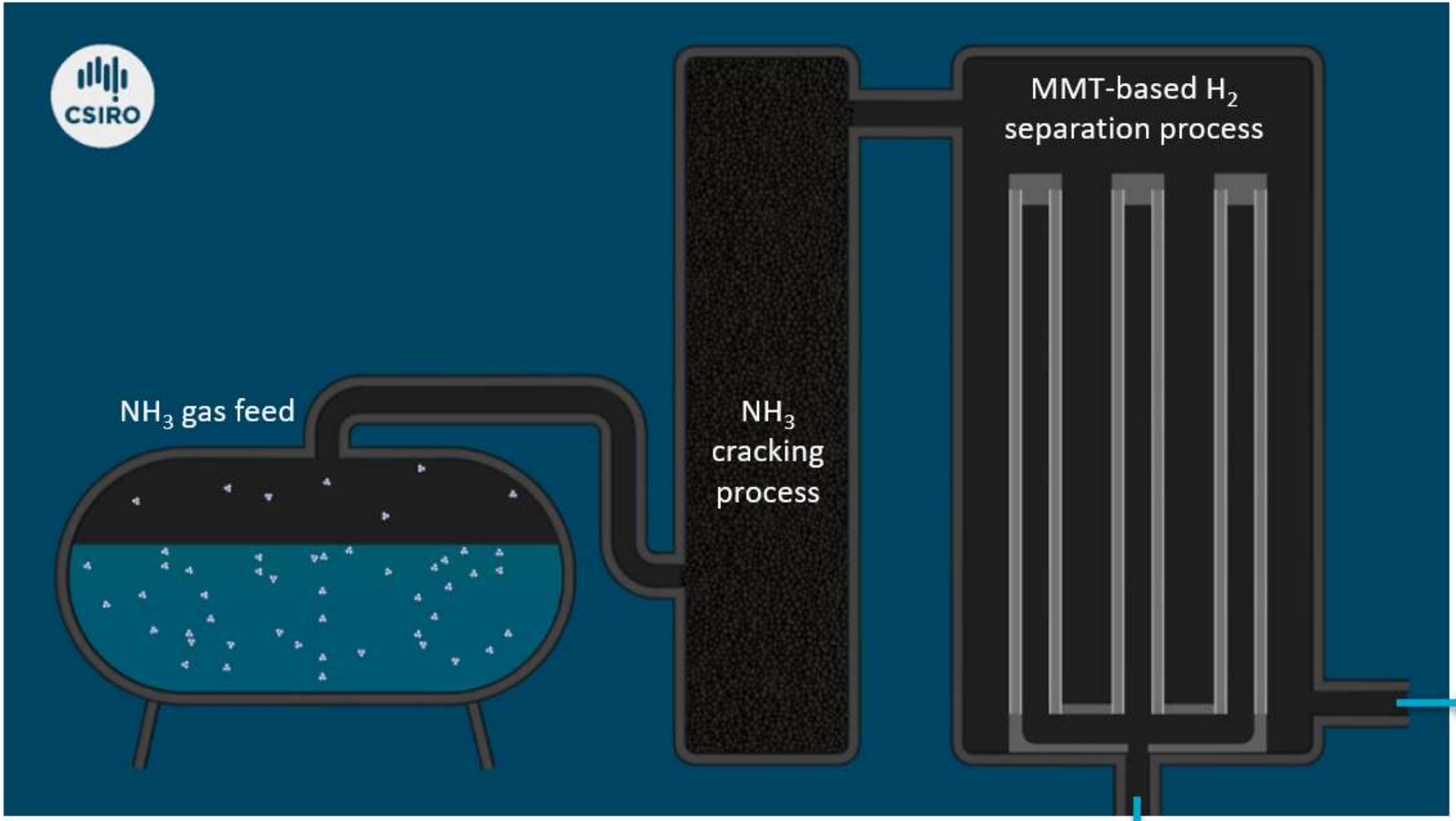
V or V-alloy core

Permeate-side catalyst (Pd)

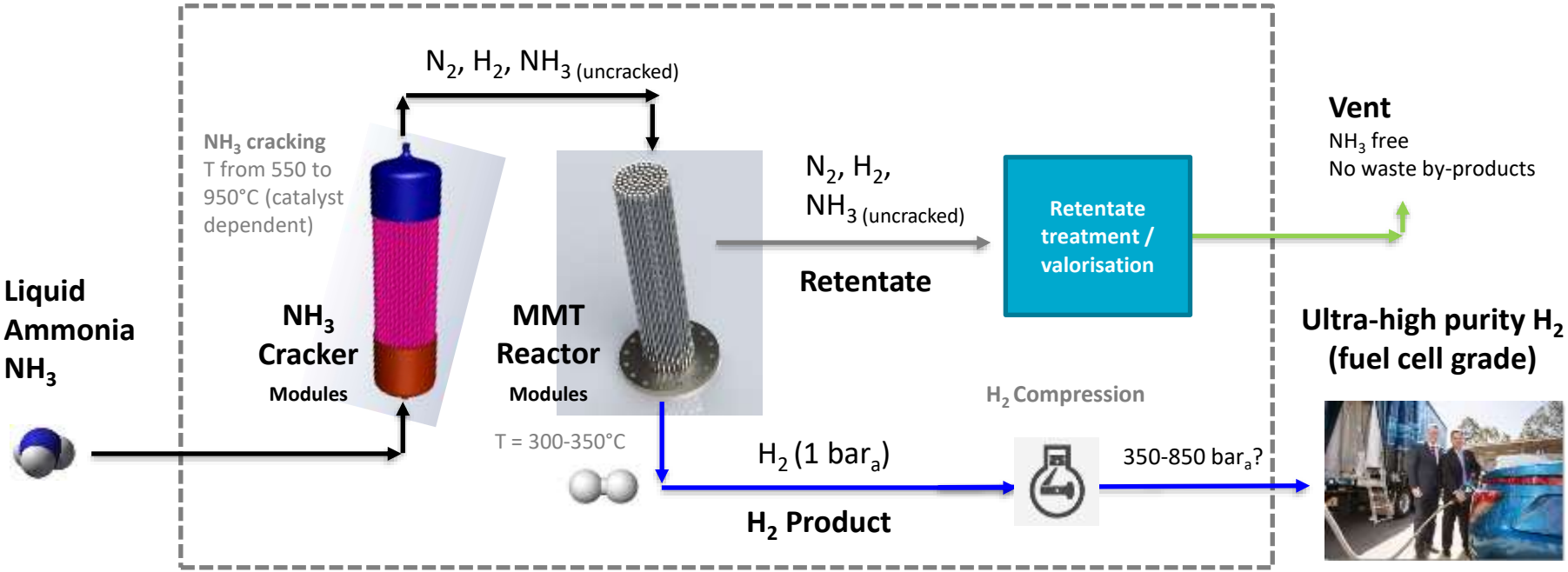
Low pressure +
Ultra-Pure H_2

Our design philosophy:

- Minimise materials costs (minimise use of palladium)
- Use scalable manufacturing techniques (metal tube extrusion and electroplating)
- Prioritise purity over flux (to meet ISO-14687 for PEM fuel cells)


MMT-based H_2 separation process
NH_3 gas feed
NH_3 cracking process
Other gases
N_2, remaining NH_3 and H_2
Product H_2
(Ultra-high purity)

Example MMT-based NH_3-to-H_2 System



Brisbane 2018 Proof-of-Concept Demonstration

World-first demonstration of FCEV-refuelling using NH_3-derived H_2 in 2018

2018 proof-of-concept NH_3-cracking and H_2 separation system

Metal membrane assembly

Brisbane 2018 Proof-of-Concept Demonstration

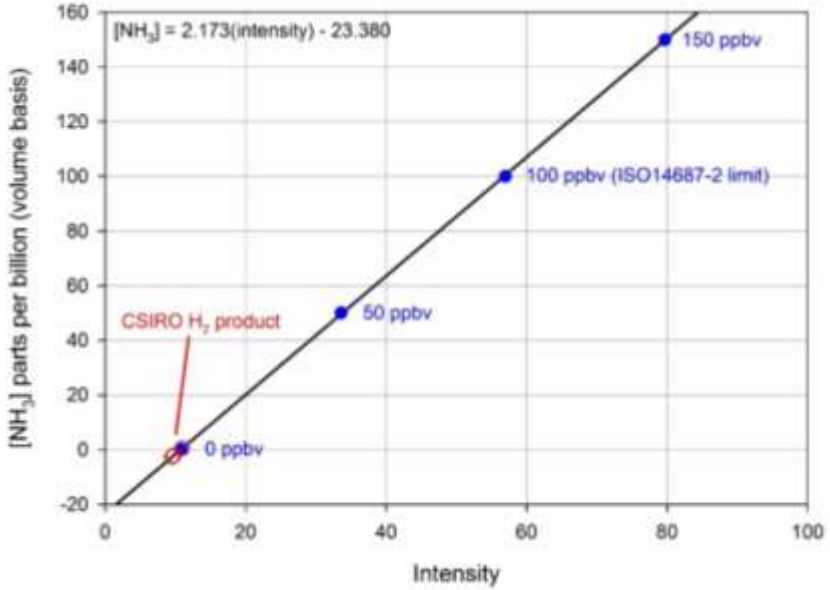
SCIENCE AND
INDUSTRY
ENDOWMENT
FUND

Supported by BOC, Toyota, Hyundai

Hydrogen purity analysis

H_2 purity for FCEV use specified by ISO 14687-02

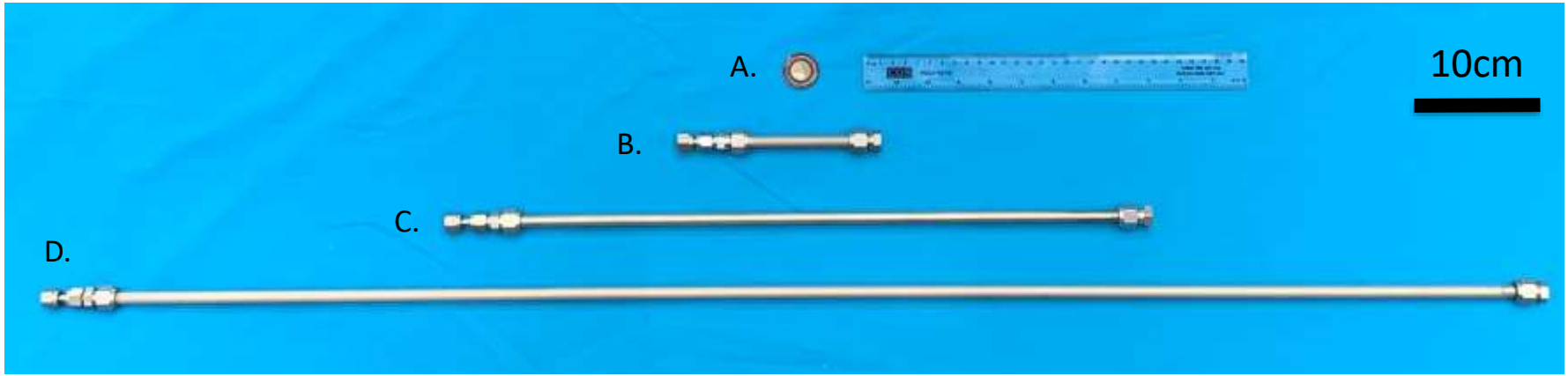
Trailer-mounted SYFT Voice 200 Secondary Ion Flow Tube Mass Spectrometer (SIFT-MS)



- Calibrated against 4.7ppmv certified NH_3-in-H_2 mixture supplied by BOC, diluted on-demand with UHP-H_2
- Detection limit << 10 ppbv
- SIFT-MS not suitable for online field applications: FTIR is best option

Technology Updates since 2018

Scaling up the manufacturing – form factor, quantity and quality



A. *2012-13* – planar membranes, 20c sized coin

B. *2013-17* – 100mm tubular membranes

C. *2017-18* – 350-500mm tubular membranes

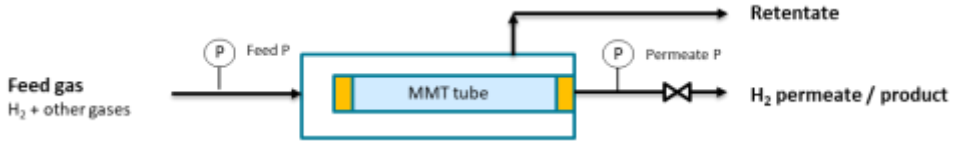
‘Bespoke’ manufacturing

D. *2019-current* – 1100mm tubular membranes, with greater scale and quality control

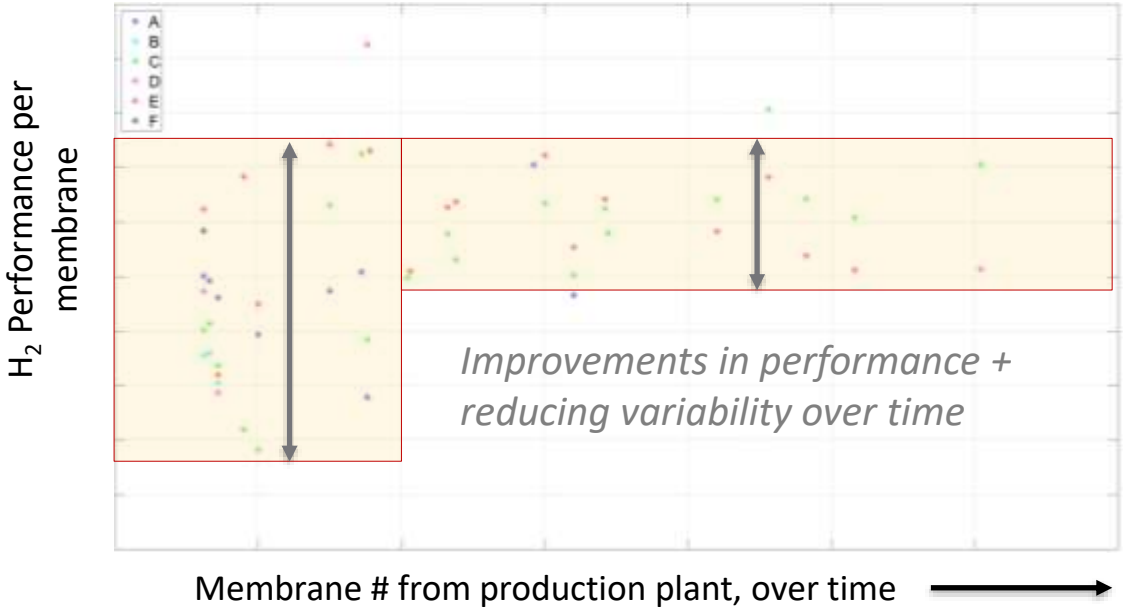
→ Automated manufacturing

Quality control

- Automation providing greater reproducibility, repeatability and quality control
- Monitoring of performance (e.g. H_2 permeability) over production batches

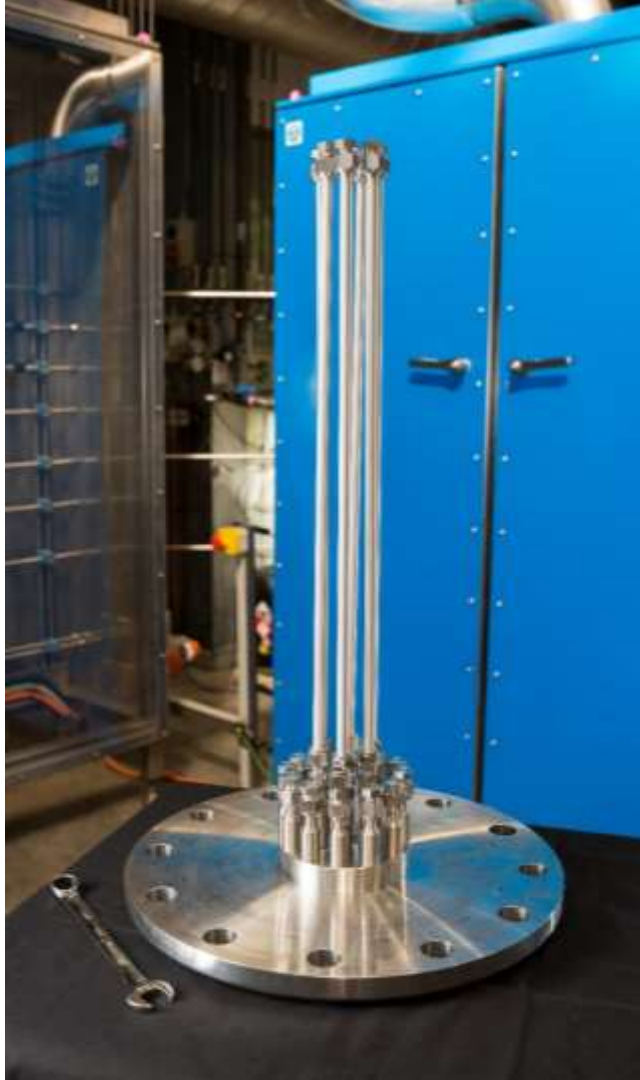


Membrane performance (H_2 permeability) vs. membrane no.



Advances in robustness

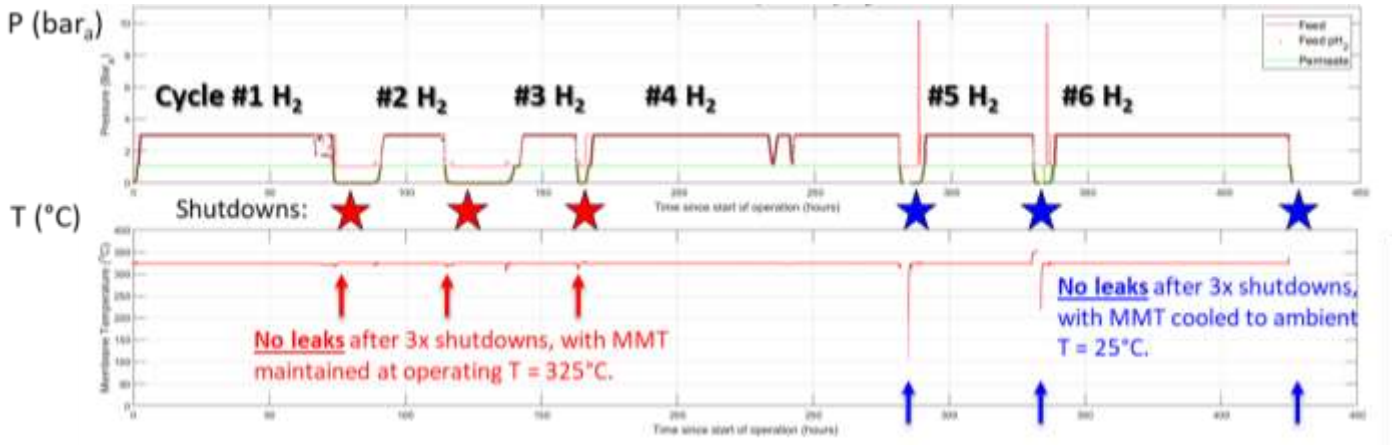
- Previous compression seals a challenge
- Latest seal technology (patents pending) provide additional robustness to the technology – importantly, preserving H_2 purity over cycles of operation



Advances in robustness

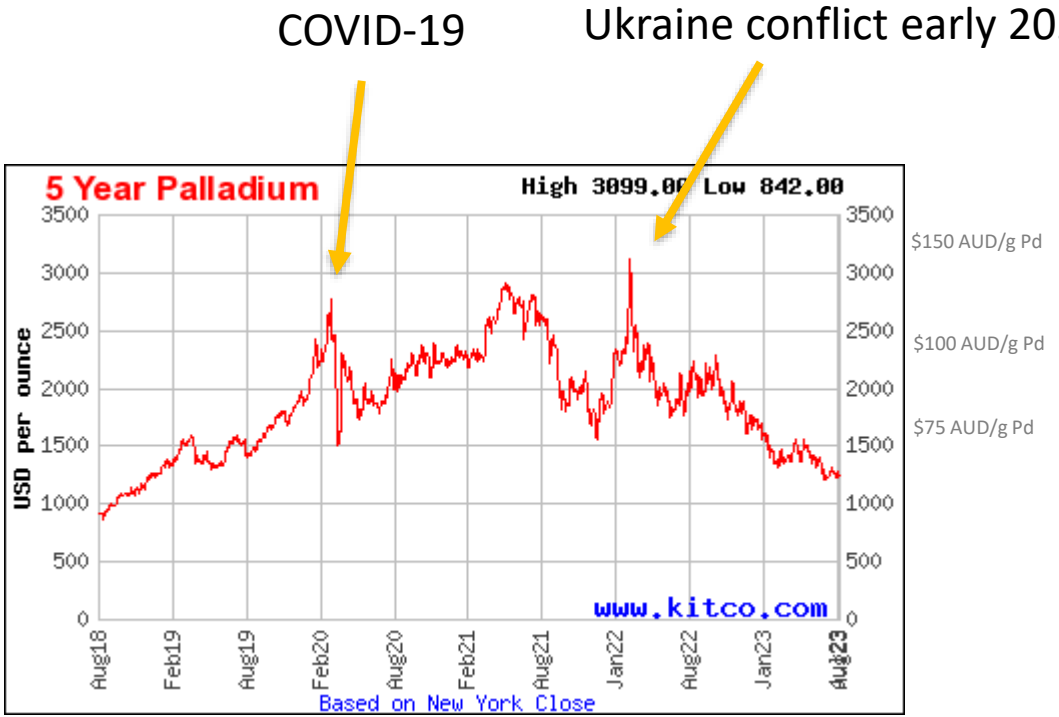
Seal integrity maintained – vacuum pressure held on membrane permeate side – after multiple cycles of H_2 operations, including shutdown + cooling to ambient.

Multiple cycles of H_2 operations on lab-scale system, with latest seals (patent pending)



Supply chain

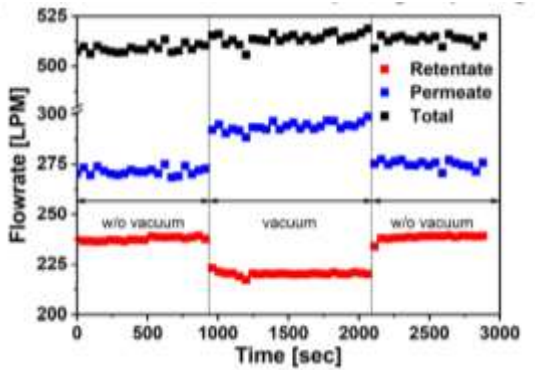
An important factor for all new technologies



https://www.kitco.com/charts/livepalladium.html

40 kg/day pilot trial

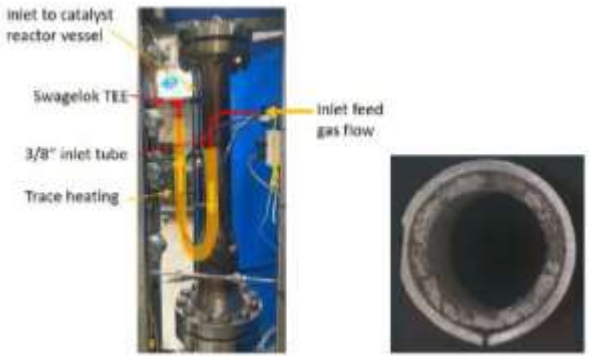
- Consortium with CSIRO, FFI and partners
- Successful trial in 2022 with 40kg/day pilot ammonia cracker + MMT purification module
- H_2 produced with no N_2 / NH_3 leaks (per GC / FTIR analysis)



Siemens Energy pilot – 200 kg/day

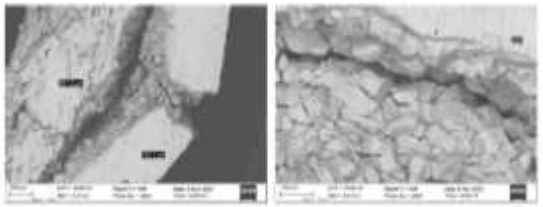
- Siemens Energy led consortium – including Geopura, Fortescue and CSIRO
- Ammonia cracker system prototype, designed to produce fuel-cell grade H_2 from green NH_3 via MMT purification module
- Testing two 100 kg/day modules
- Commissioning end-2023 / early-2024

Safety Share – Nitriding by high temperature NH_3



Failed tube location

Cross-section



SEM imagery at failure

What happened?

- In 2022, minor NH_3 leak (ppm levels) in a ventilated ammonia-to-hydrogen pilot system. Triggered gas detection systems and safe shutdown of the plant. No exposures/injuries.
- **SS316 tube failed due to severe nitriding attack** after 2000 hours operation, under high temperature (>450°C) and ammonia partial pressures (pure NH_3, 10 bar_g)

What we learnt?

- **Carbon steel and stainless steels highly susceptible to nitride attack > 300°C, and particularly with NH_3 gas concentrations >30%**, worsened through thermal cycles.
- Nitriding can cause embrittlement and tube failure if severe enough. Rate of nitriding here was ~2-3 mm/year, higher than expected in literature (likely due to thermal cycling).
- Ammonia industry manages this with appropriate metallurgy / materials selection, plant design, condition monitoring + risk based inspection, and can achieve >20y service lifetimes.

Recommendations – particularly to R&D community in the ammonia space:

- Avoid nitriding conditions in plant design, and avoid thermal cycling / shock
- In severe nitriding conditions (>30% NH_3, T >300°C), use >50% Ni (e.g. Alloy600) or Ni-Co alloys
- Best practice – engage industry practitioners (ammonia industry) on materials selection
- Perform regular inspections of areas at risk of nitriding

Towards commercialisation

- Fortescue is the commercialisation partner and exclusive licensee of CSIRO's Metal Membrane Technology (MMT).
- Next scale up at 200 kg/day pilot demonstration
- Whilst focus is on FCEV-grade H_2 from cracked ammonia, MMT can be used for H_2 separation from other mixed gas feeds (*noting limitations with specific impurities)

Thank you

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