HYDROGEN RECOVERY FROM EUV LITHOGRAPHY

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Systems and Solutions

Edwards Limited

Hydrogen Recovery

- Background
- Technology Selection
- Explanation of Technology
- Test results (performance and lifetime)
- Use of recovered hydrogen
- Environmental benefit
- System design

Gas Recovery from Semiconductor Processes
- Not A New Idea -

- Semiconductor processes often do not use materials efficiently
  - Unused material leaves the process chamber
    - Unreacted
    - As some kind of by-product
  - That’s why we need abatement
- Several projects over many years to recover materials
  - CF4, F2, SF6, Xe…
  - All have been made to work
  - None have been commercially viable
    - Complexity results in cost and risk
    - Cost and risk exceeds benefit value
- But EUV Lithography may be different
  - Why?
  - How?

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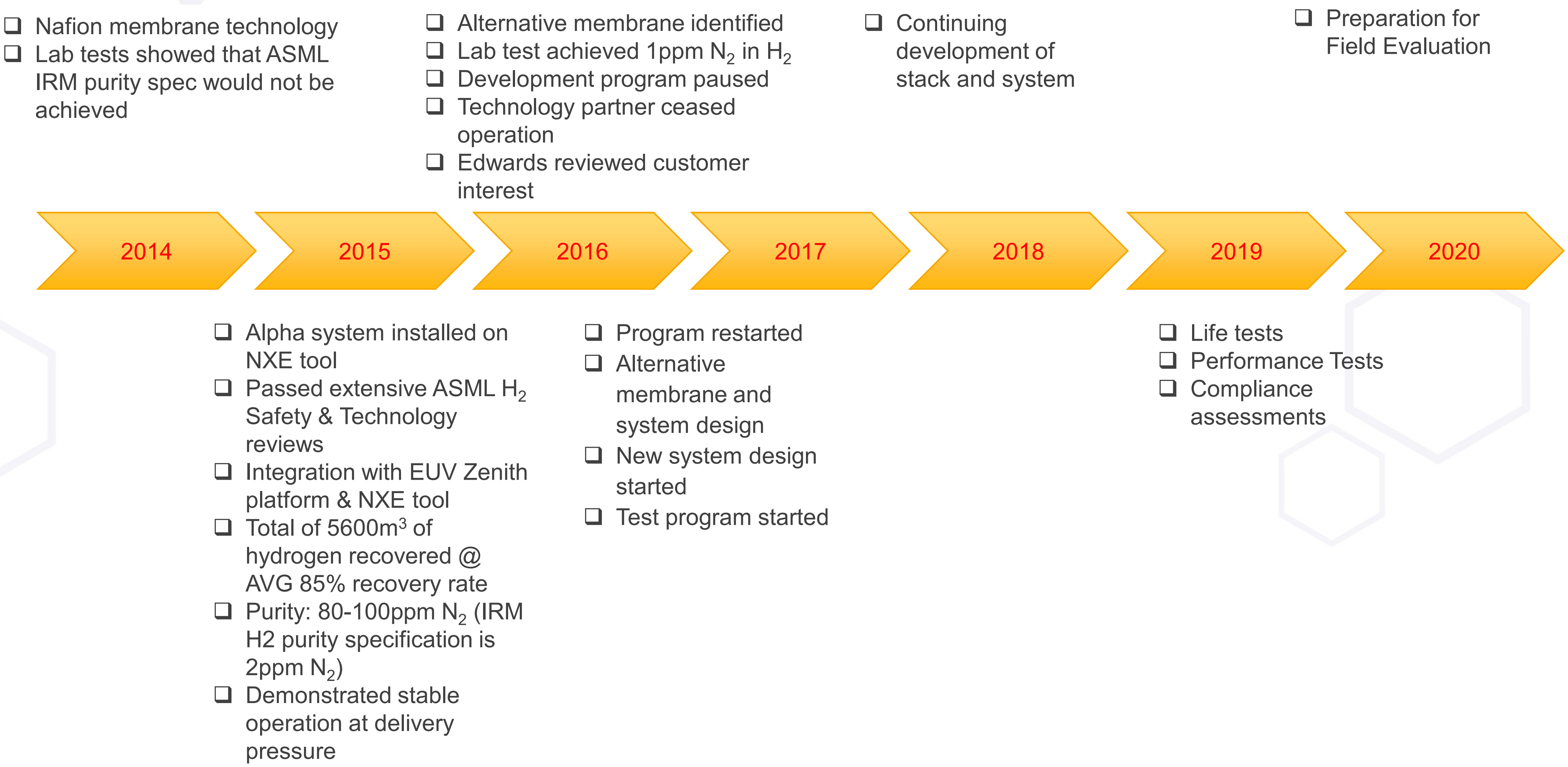
Why Now? Why EUV Lithography?

- High usage rate creates a real problem
  - Significantly higher consumption than regular processes
  - Continuous high flow
    - X 20 compared to Epi chamber
  - Supply logistics / capacity
  - Safety
- Simple duty cycle makes solution possible
  - Continuous H2 flow
  - Simple chemistry – no corrosives, condensables, pyrophorics
  - Just need to separate H2 from N2
  - Hydrogen
    - Small molecule size offers more separation technologies
  - Disruptive
    - New investment in EUV Lithography installations creates opportunity

EUV HRS Project Timeline



2014

- ❑ Nafion membrane technology
- ❑ Lab tests showed that ASML IRM purity spec would not be achieved

2015

- ❑ Alpha system installed on NXE tool
- ❑ Passed extensive ASML H_2 Safety & Technology reviews
- ❑ Integration with EUV Zenith platform & NXE tool
- ❑ Total of 5600m^3 of hydrogen recovered @ AVG 85% recovery rate
- ❑ Purity: 80-100ppm N_2 (IRM H2 purity specification is 2ppm N_2)
- ❑ Demonstrated stable operation at delivery pressure

2016

- ❑ Alternative membrane identified
- ❑ Lab test achieved 1ppm N_2 in H_2
- ❑ Development program paused
- ❑ Technology partner ceased operation
- ❑ Edwards reviewed customer interest

2017

- ❑ Program restarted
- ❑ Alternative membrane and system design
- ❑ New system design started
- ❑ Test program started

2018

- ❑ Continuing development of stack and system

2019

- ❑ Life tests
- ❑ Performance Tests
- ❑ Compliance assessments

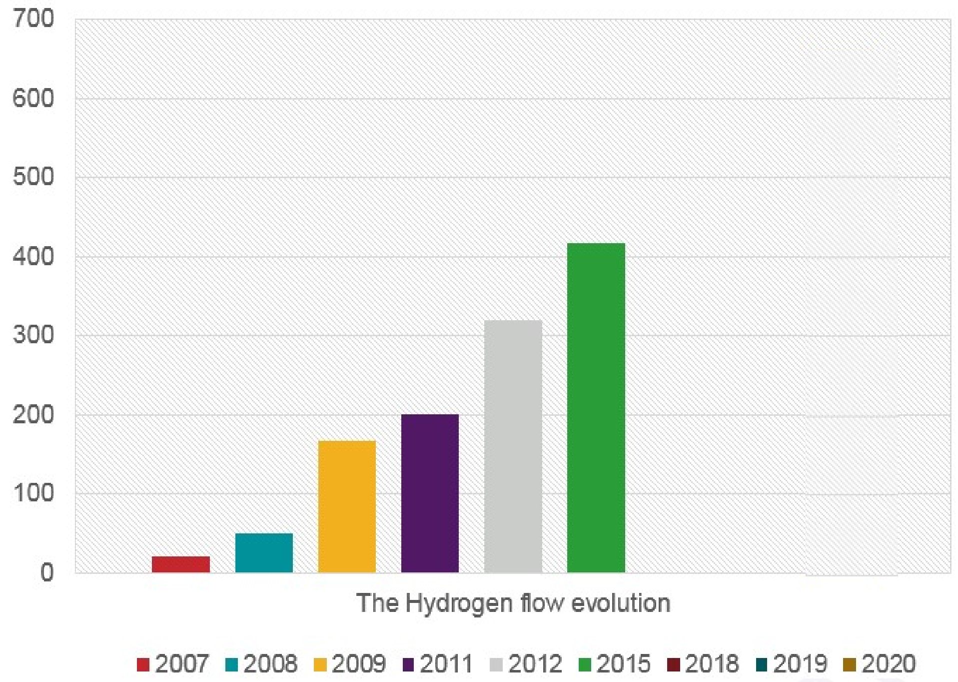
2020

- ❑ Preparation for Field Evaluation

EUVL Hydrogen Flow Rates

- ASML NXE development
- 3100, 3300, 3350, 3400…

- Hydrogen is used in the Source and the Scanner
  - Low transmission loss
  - High heat transfer capacity
  - Reacts with Tin (Sn)
- Flow rate driven by Source requirements



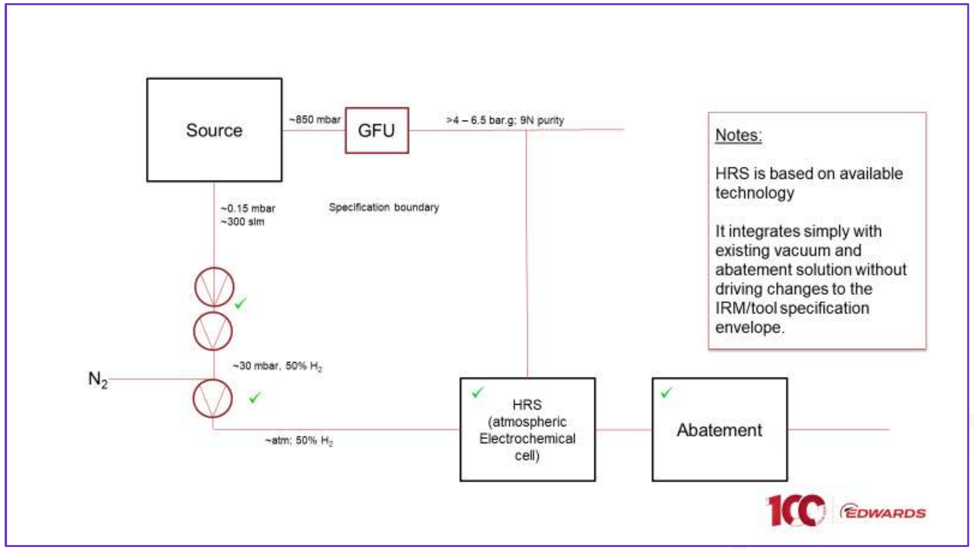
	H2 Flow Rate	Contaminant	Value - Cost
Source	High (~ 400slm)	Nitrogen, Tin	+ ve
Scanner	Low (~ 17slm)	Nitrogen, Photoresist outgas products	- ve

What Happens To The Tin?

- Hydrogen reacts with Tin (Sn) in the Source to form Tin Hydride (Stannane)
- Tin Hydride will plate out on warm surfaces
- The vacuum system incorporates Tin traps to catch the Tin
  - To protect the pump
  - To prevent Tin discharge
- No Tin reaches the abatement system
- Therefore no Tin will reach the recovery system
- Ongoing plan to monitor Tin content of exhaust stream
  - Mitigation – if Tin is found > increase Tin trap residence time

Why choose Electrochemical Technology?

- Available technology options
  - Electrochemical
  - Physical separation (e.g. hot Palladium membrane)
- Electrochemical compared to physical separation technologies
  - No additional compression needed
  - Reasonable size
  - Reasonable cost
  - Benign failure modes
- Outcome
  - Electrochemical technology selected



Notes:

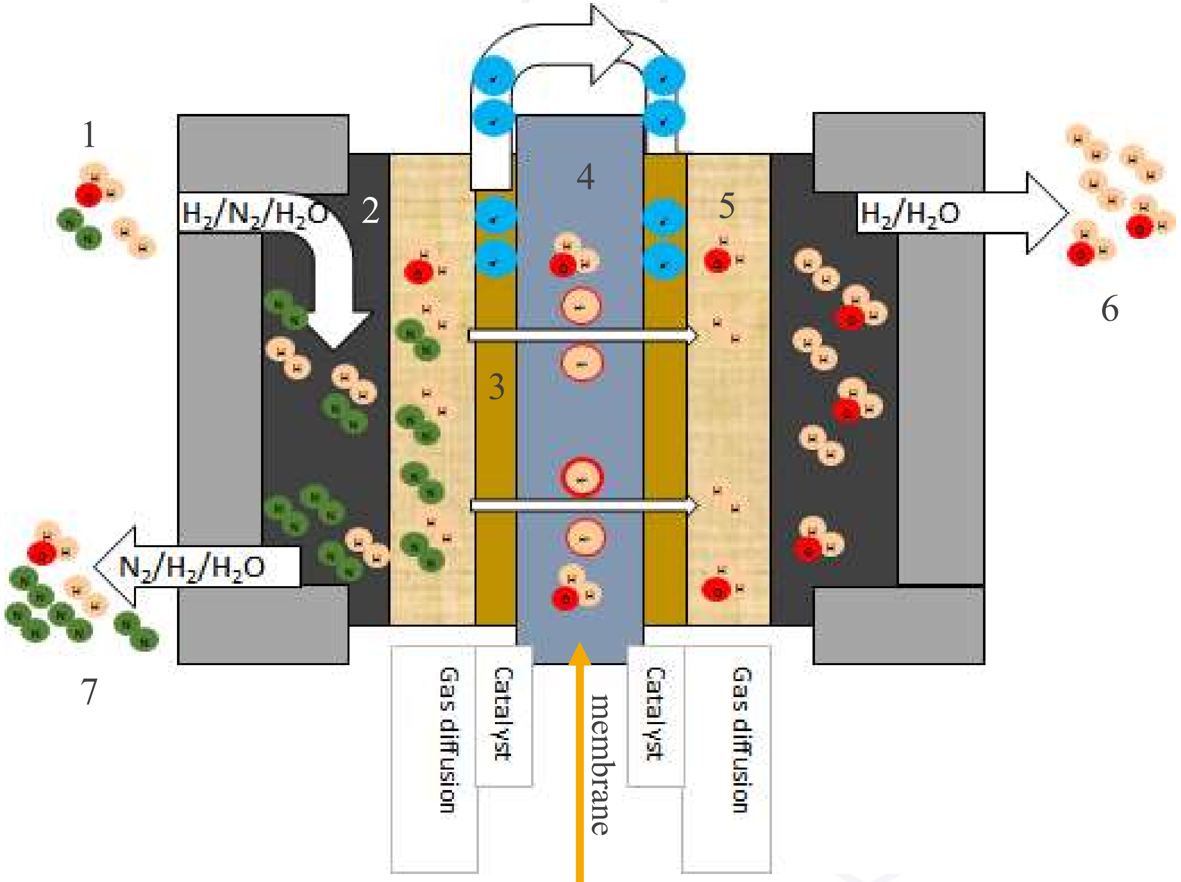
HRS is based on available technology

It integrates simply with existing vacuum and abatement solution without driving changes to the IRM/tool specification envelope.

- Alternative sites for recovery
  - Vacuum
  - Atmospheric
- Electrochemical efficiency increased with anode pressure
- Outcome
  - Atmospheric pressure selected

Electrochemical Cell

1. Gas (nitrogen/hydrogen/water) is pumped/drawn into the cell.
2. The gas diffuses through the diffusion layer (GDL)
3. The hydrogen is oxidised on the anode electrochemical catalyst, reacting with water to produce hydrogen ions.
4. These positive ions migrate, under an electrochemical potential, from the anode to the cathode through a perm-selective membrane as hydrated ions.
5. They are the reduced on the cathode electrochemical catalyst to hydrogen gas and water.
6. Water is removed as the final purification stage.
7. Waste gas goes for abatement.



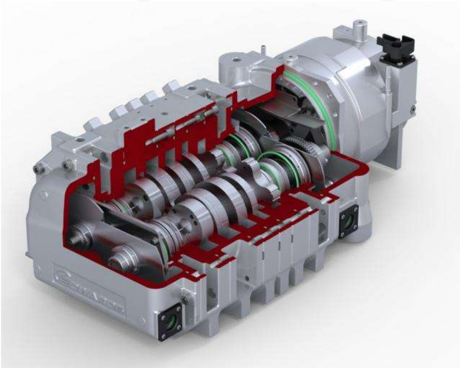
Only protons and water pass through membrane.

Nitrogen and all other gases are blocked

Why Add Nitrogen?

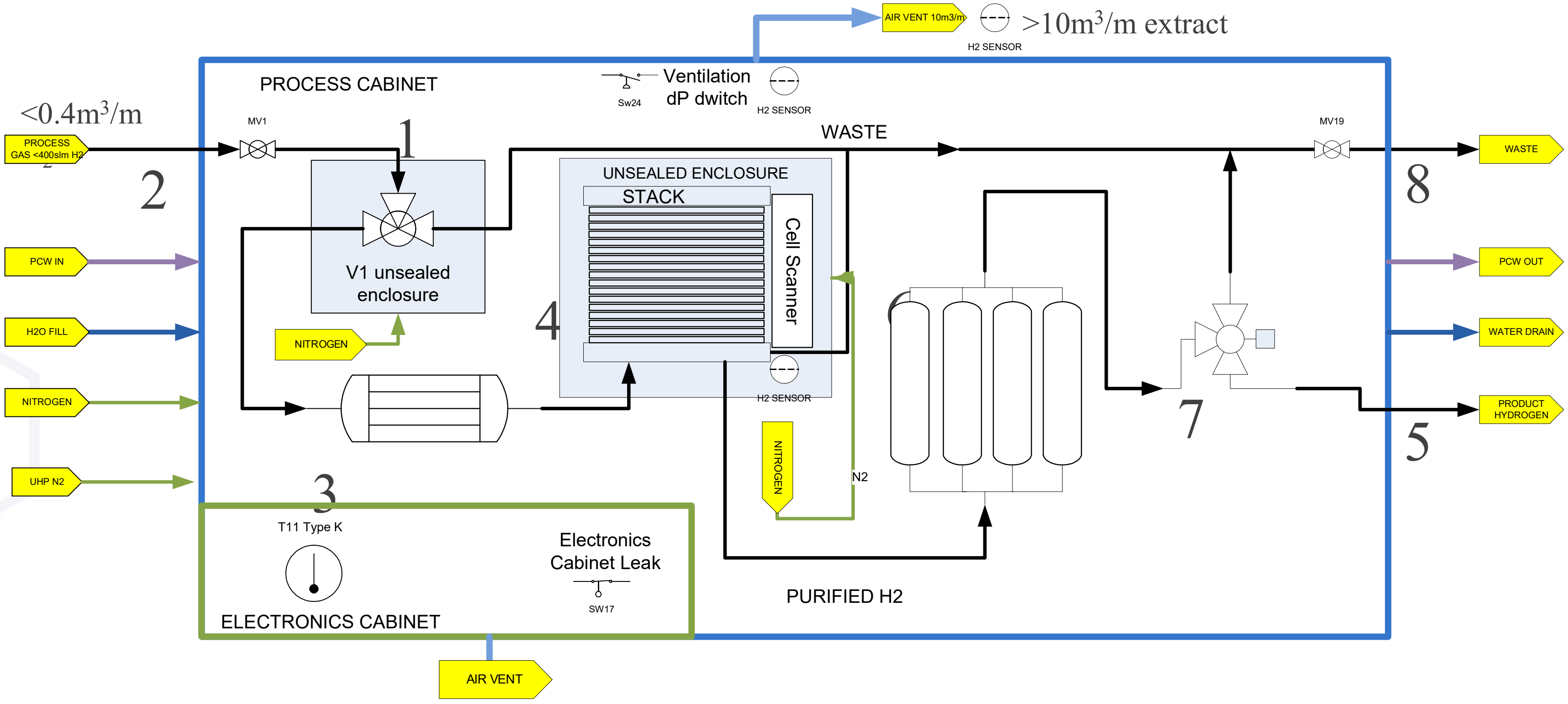
- Hydrogen is a major challenge for dry pumps
- There is no oil to seal the compression stages (more than 1000:1)

Gas	RMM	Viscosity @ 20°C Pa.s	Thermal Conductivity @ 20°C W/m/K
Air	29	$1.82 \cdot 10^{-5}$	0.024
Nitrogen	28	$1.76 \cdot 10^{-5}$	0.024
Hydrogen	2	$8.80 \cdot 10^{-6}$	0.18
Helium	4	$1.96 \cdot 10^{-5}$	0.15

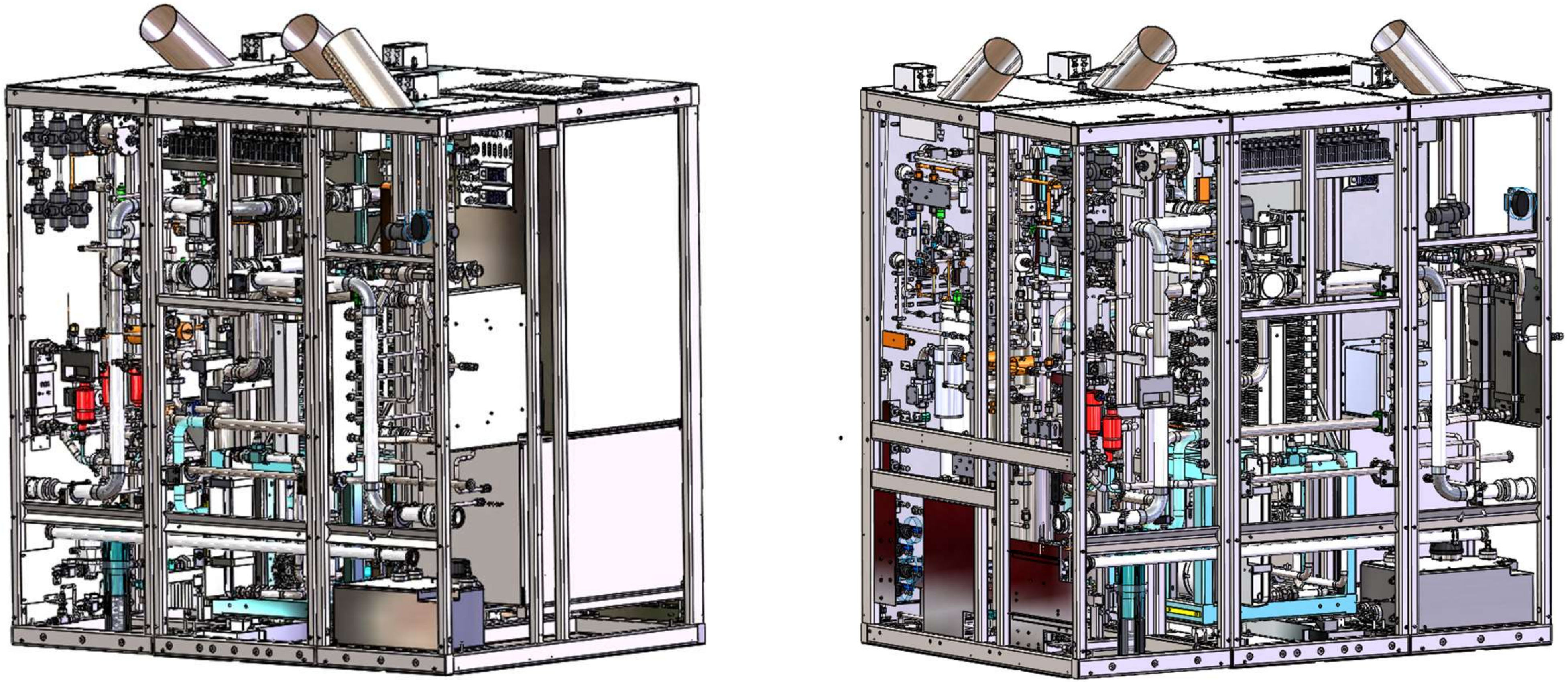


- Low RMM means increased back-leakage, particularly in molecular flow (less than 10^{-3}mbar)
- Low viscosity means increased back-leakage in continuum flow
- High thermal conductivity means better heat transfer between rotor and stator
  - ➢ Lower temperature difference > Bigger clearance
  - ➢ More back leakage > MUCH higher motor power
- Add gas with higher RMM and viscosity and lower thermal conductivity that does not react with process gas
  - ➢ Add Nitrogen after first stage of compression for suppression of back-streaming

Hydrogen Recycling System Schematic

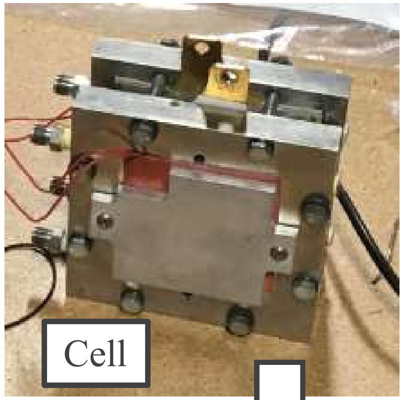


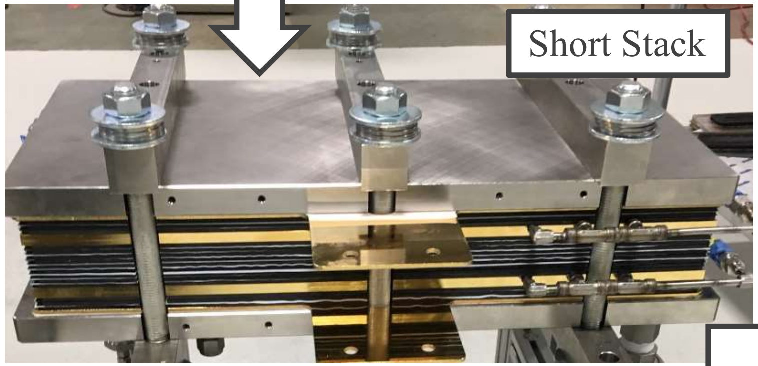
Hydrogen Recycling System



Scale-up of electrochemical technology

- Single electrochemical cell is impractical for large scale pumping
- Instead, multiple cells are stacked together with a parallel gas path form a 'stack'
- Using the stack method, electrochemical pumps are built capable of handling any flow rate desired
- Individual cell testing is still an important tool for R&D of novel designs & materials



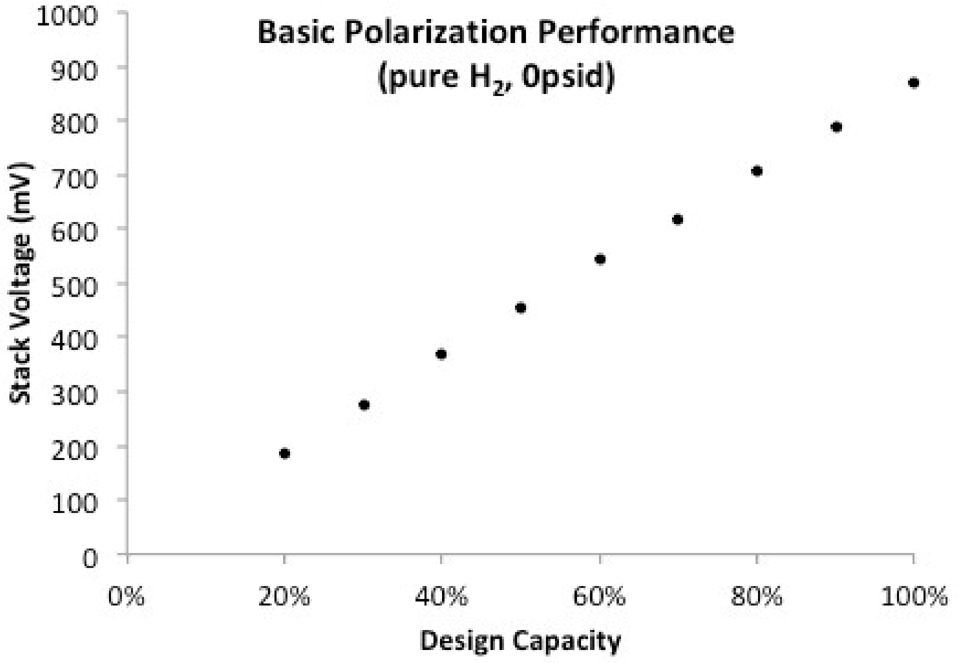


240x more surface area vs. cell

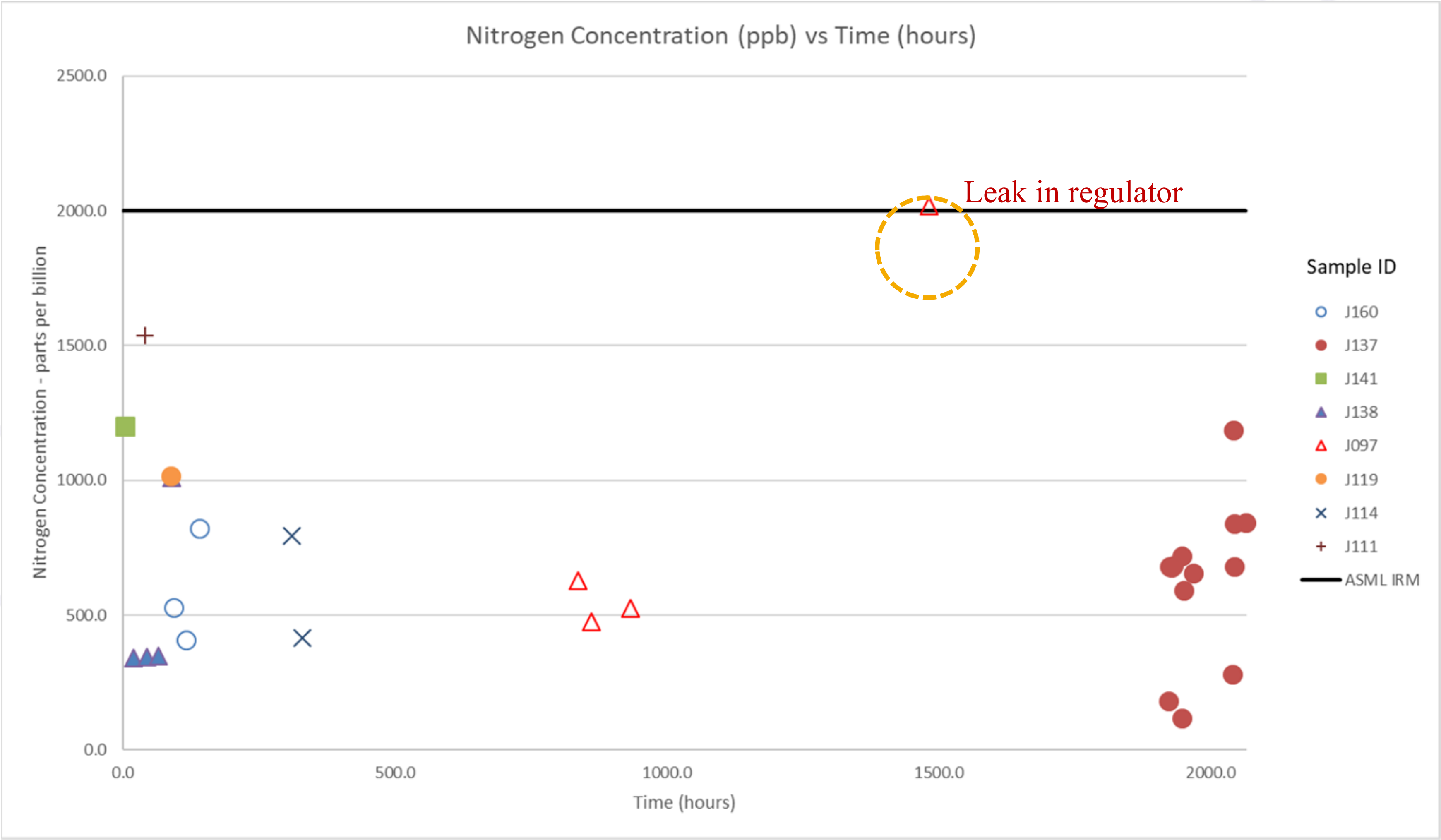
5x more surface area vs. short stack

Performance Test Results

- **Stack electrochemical performance matches small test cell results**
  - – Impedance (membrane conductivity) meets or exceeds test cell results
    - Maximizes system efficiency
  - – Basic Polarization: linear within full operating window
    - Performance as designed
    - No unaccounted over-voltages (inefficiencies)
    - Good gas flow distribution within stack
- **Key Metrics of Product Gas:**
  - – 140psig
  - – <2 ppm nitrogen impurity concentration
  - – No gas leaks found outside stack or thru the cell membranes --- no escaping hydrogen



Hydrogen purity of product gas



Anode Feed Gas:
35-45% N_2
Balance H_2

H_2 Recovery: 83%

Quality of Hydrogen Returned from HRS

Impurity Concentrations of High Purity Hydrogen

Hydrogen Source	**Argon**	**CO_2**	**CO**	**He**	**N_2**	**O_2**	**H_2O**	**THC**
CGA gas standard: High purity liquid H_2	1	2		-	2	1	3.5	1
Praxair semi-con grade gaseous H_2 standard	-	0.1	0.1	-	0.5	0.5	0.5	0.1
HRS recovered H_2**	-	-	-	-	<2	-	<0.001	-

Units: parts per million

- = no quantification yet

** = No sources of Ar, CO, CO_2, He, O_2 or THC in HRS source gas. No quantification of these gases attempted

HRS Lower Detection Limits:

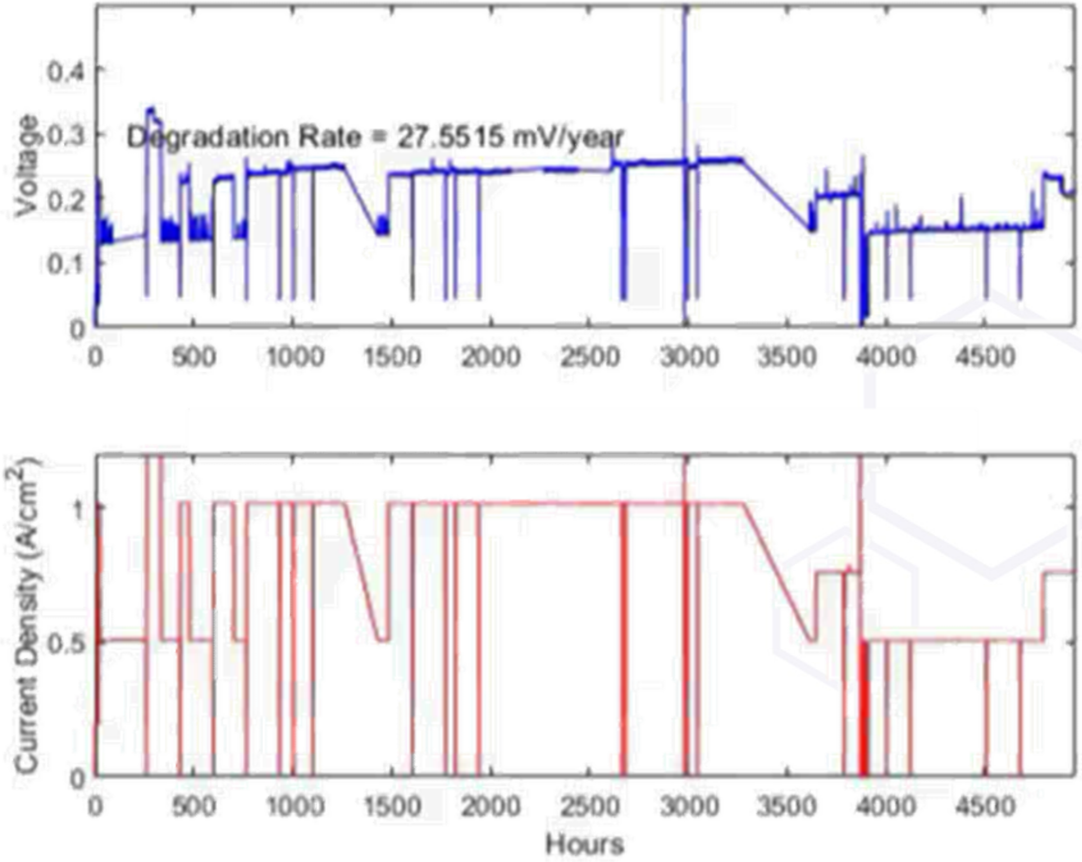
N_2	H_2O
0.010	0.001

Units: parts per million

Electrochemical Aging Tests

- Electrochemical membrane slowly loses conductivity over time
  - Creates a voltage increase
- Voltage increase leads to more heat generation within stack
  - No loss of purity, but less efficient, more waste heat
  - Want to <u>minimize</u> this voltage increase
- Average voltage increase is 50 mV/year
  - Correlates to ~ **2+ year** life time
  - Life time determined by system ability to reject waste heat, and customer tolerance for energy inefficiency.
  - Pump doesn't simply stop pumping or lose purity
- Improvements in design & materials made during R&D suggest we can achieve 25 mV/year (doubling stack life)
  - Testing ongoing

Voltage degradation rates over ~ 6 months.

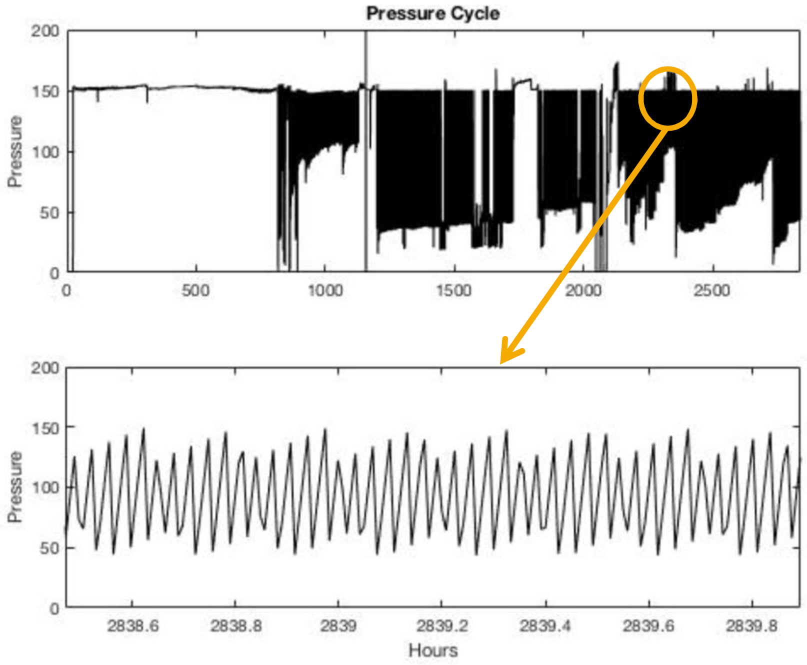


Current controlled by power supply

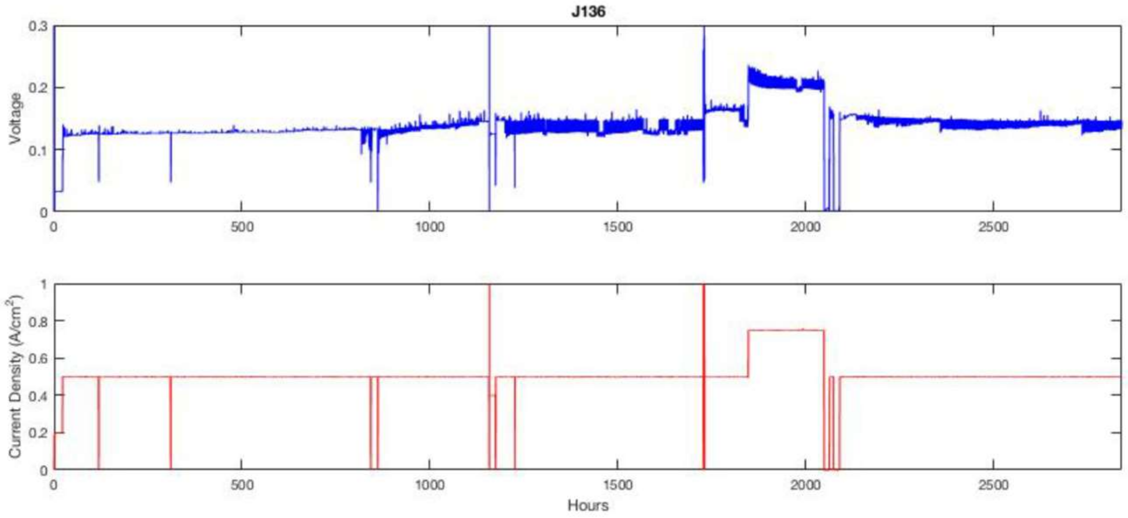
Accelerated Mechanical Stress Tests

- Expansion & contraction on electrochemical membrane may cause degradation
- Accelerated mechanical stress test conducted to evaluate risk
  - Normal operation: Pressure swing = 20 psi, every 24 minutes. ~22,000 pressure swings/year
  - Accelerated stress test: Pressure swing = 100 psi, every 2 minutes. On pace for ~ 260,000 swings/yr
- Accelerated test results thus far: **No issues** after > 70,000 pressure cycles of 100 psi.
  - Minimum 3 year mechanical life (potentially much more)

Mechanical Performance



Electrochemical Performance



Voltage and Current readings for cell under pressure cycled – no degradation.

Summary of Test Results

- >80% H_2 recovery
- >140 psi_g recovered H_2 delivery pressure
- <2 ppm nitrogen in recovered H_2
- Dehumidification of H_2 product to below -120°C dewpoint
- Meets ASML IRM requirements for N_2 and H_2O
- Stack lifetime tests indicate greater than 2+ years lifetime
- Testing continues

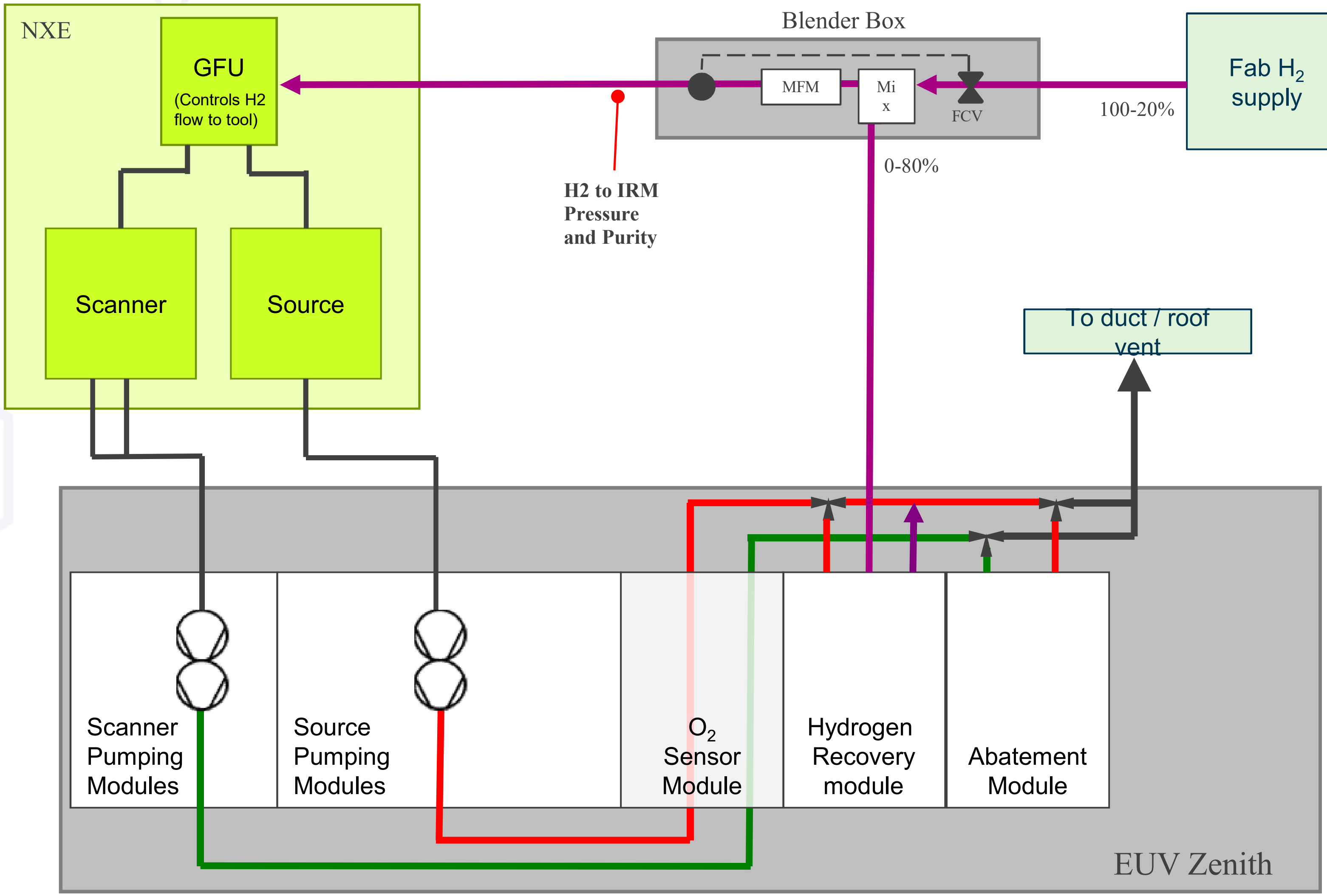
Summary

- Hydrogen recovery from EUV Lithography Source is viable
- Electrochemical technology is good technology choice
- Performance meets ASML IRM requirements
- Life tests show good results
- Net CO_2-eq reduction

What To Do With The Recovered H_2?

- Options:
  - Return to NXE tool
    - Top up with facility H_2
  - Return to facility for use as process gas for all processes
  - Return to facility for use as fuel
    - Use in abatement
    - Use in fuel cell to generate electricity

Schematic to Return Recovered H_2 to NXE tool



Key:

ASML Scope of Supply

Edwards Scope of Supply

End User Scope of Supply

EUV Zenith sub-system operating scenarios:

Normal operation (OK State):

- 🟥 Source module => HRS
- 🟩 Scanner module => Abatement
- 🟪 Waste H_2 from HRS => Abatement

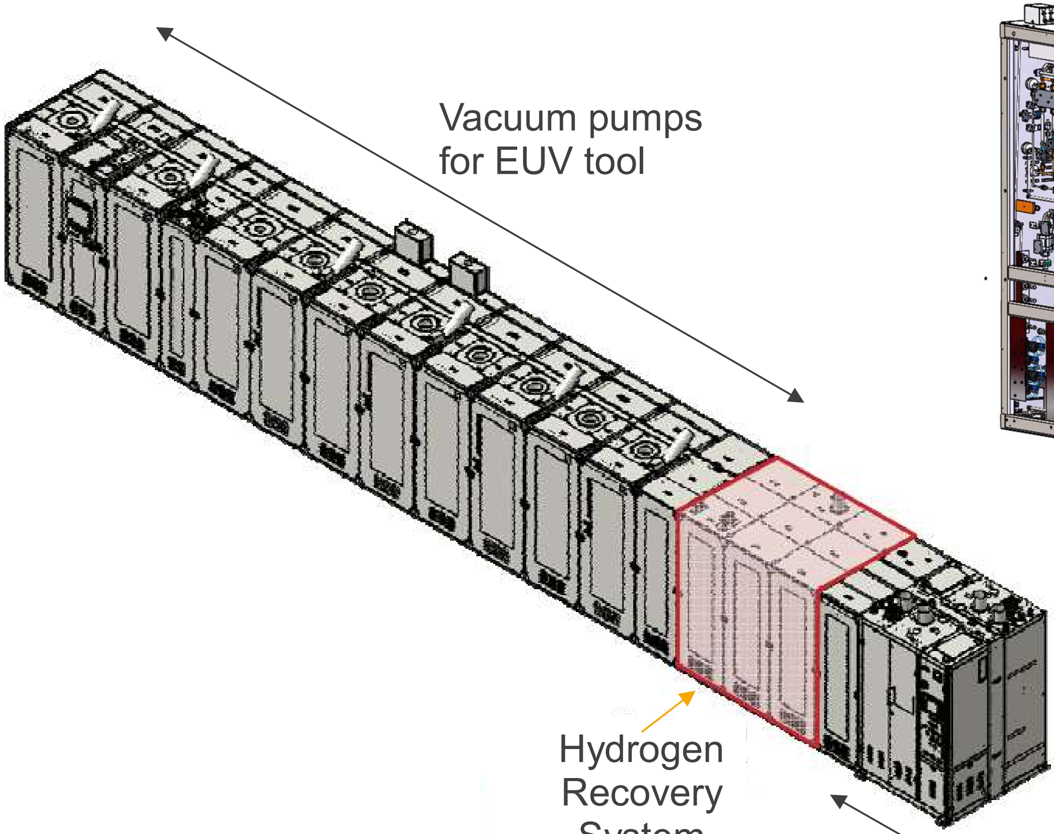
Hydrogen Recovery off-line (OK State):

- 🟥 Source module => Abatement
- 🟩 Exposure module => Abatement
- 🟪 Waste H_2 from HRS => Abatement

Abatement off-line (NOK State):

- 🟥 Source module => HRS
- 🟩 Exposure module => Dilution
- 🟪 Waste H_2 from HRS => Dilution

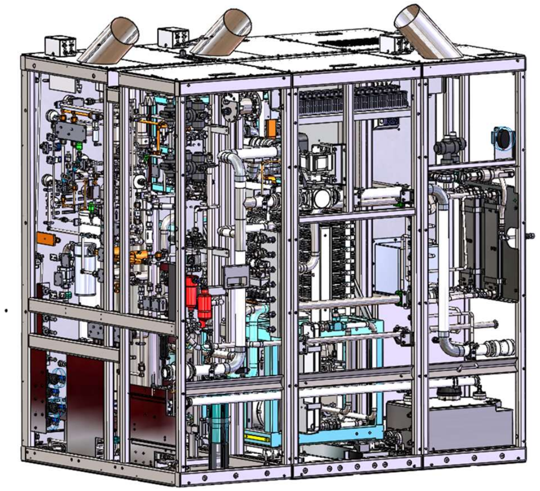
Hydrogen Recovery System Integration



Vacuum pumps
for EUV tool

Hydrogen
Recovery
System

Abatement for
EUV tool



Environmental Benefit of Re-Using Hydrogen As Process Gas

- Energy required to recover H_2
  - 5 kWh / kg H_2 recovered
- CO_2 equivalent
  - 3.5 kg CO_2 -eq / H_2 recovered

1 kg H_2 = 11123 sl

- Energy required to produce H_2
  - 11.3 kg CO_2-eq/kg H_2 to produce H_2 steam reforming
    - Source – EPA website
- Net saving of 7.8 kg CO_2-eq / kg H_2
  - More if you include reduction in downstream handling load
    - But – we plan to reduce that by other means…

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Thank You

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