Investigation of Hydrogen in Sodium and Argon Environments

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Background

Inside a Sodium-Cooled Fast Reactor

- The nuclear fission reaction in the reactor core generates large amounts of heat in fuel rods.
- This heat is removed by liquid sodium coolant circulating through the reactor core.

Sodium Heat Extraction Process

- Primary sodium loop:
- Hot liquid sodium flows around fuel assemblies, absorbing the fission heat.
- The temperature rises to about 525 °C at the reactor outlet.
- The heated sodium transfers energy to the secondary sodium loop through an intermediate heat exchanger (IHX).
- This separation ensures that radioactive primary sodium never contacts water or steam directly.

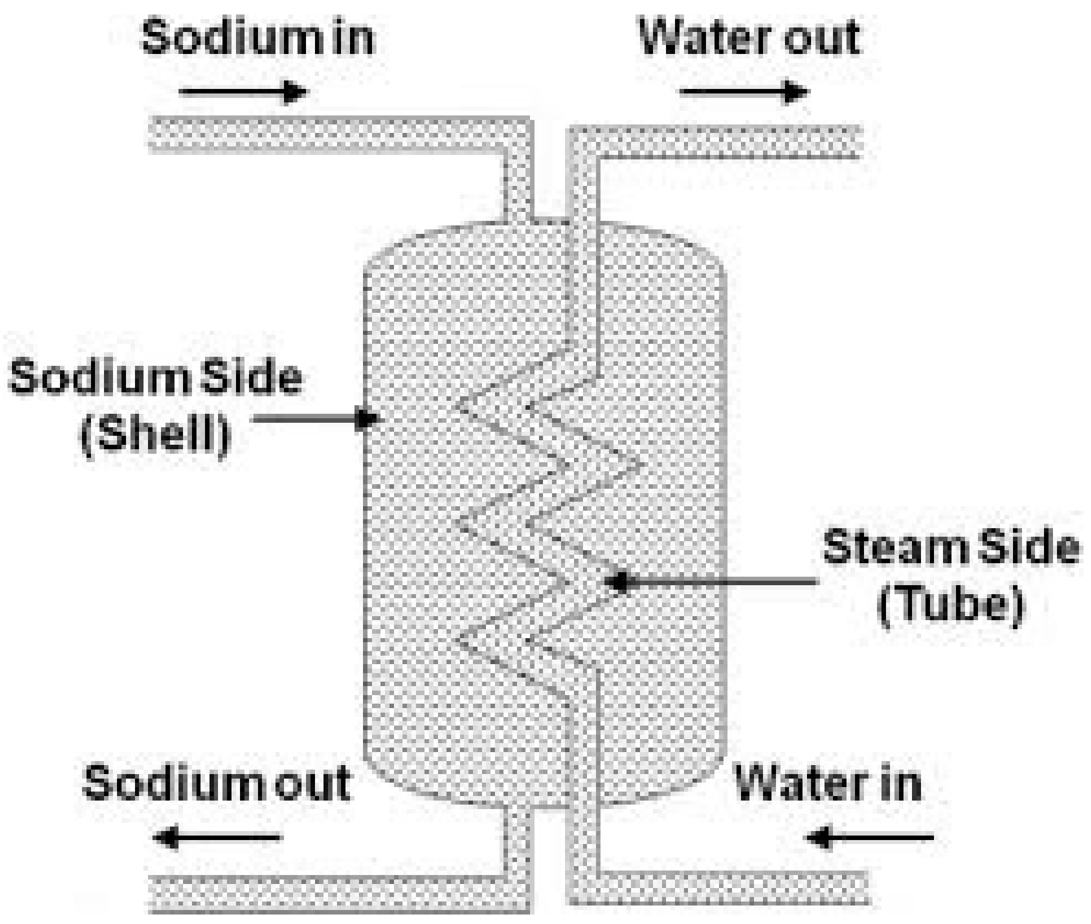
Background

Steam Generation

- In the secondary loop, cooler sodium (≈ 355 °C at inlet) flows in the opposite direction.
- The heat is transferred from sodium to high-pressure water (≈ 150 bar) in the steam generator, producing superheated steam for the turbine.

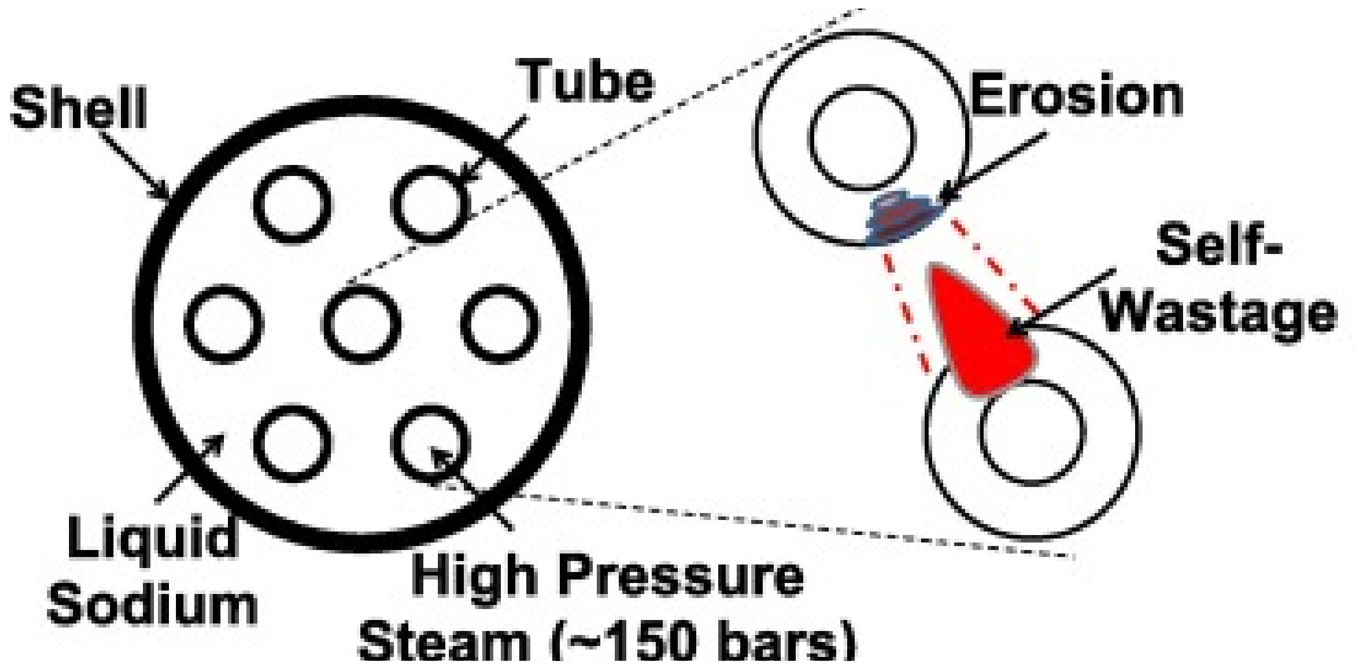
Opposite Flow Mechanism

- Sodium and water/steam flow in counter-current directions across thin-walled ferritic steel tubes (~3–4 mm thick).
- This ensures efficient heat exchange and a strong temperature gradient, maximizing thermal efficiency.



Background

- A tube defect allows high-pressure steam to leak into hot sodium, triggering the sodium–water reaction.
- The reaction forms corrosive NaOH, which attacks the leaking tube.
- This corrosion widens the leak and promotes self-wastage of the tube material.
- The large pressure gradient and NaOH further erode nearby tubes, causing rapid damage propagation.



Background

Sodium-cooled fast reactors (SFRs) use liquid sodium as coolant and argon as cover gas.

Steam leaks in the sodium-water heat exchanger cause immediate Na–H_2O reactions:

$$2Na + 2H_2O \rightarrow NaOH + H_2$$

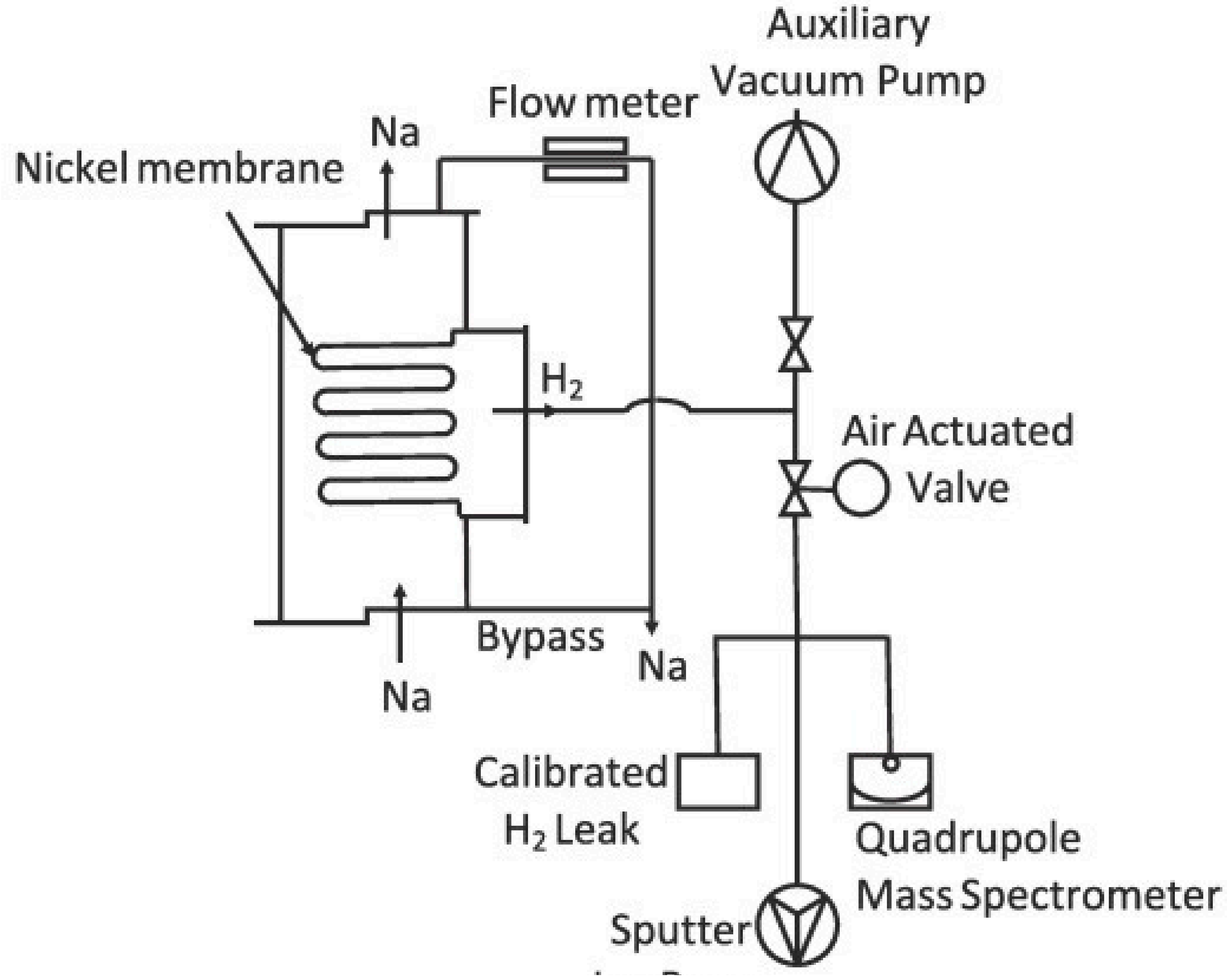
The generated hydrogen either:

- Escapes to argon cover gas (low T).
- Dissolves in liquid sodium (high T)

$$Na_{Excess} + NaOH \rightarrow [O]_{Na} + [H]_{Na}$$
$$Na_{Excess} + H_2 \rightarrow [H]_{Na}$$

Early detection of H_2 is critical for reactor safety and avoiding tube rupture propagation.

CDHM Sensor

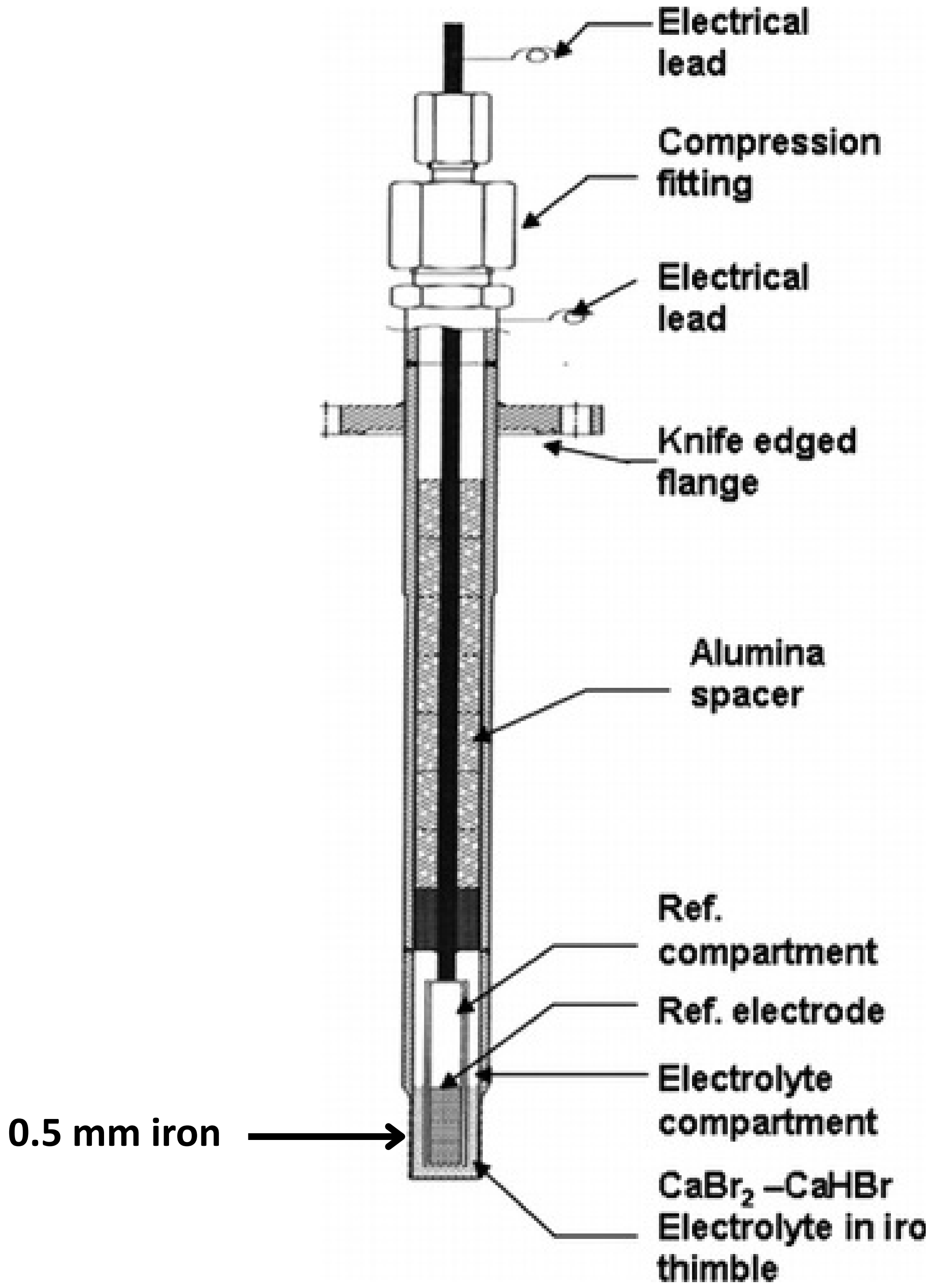


Auxiliary
Vacuum Pump
Flow meter
Na
Nickel membrane
H_2
Air Actuated
Valve
Bypass
Na
Na
Calibrated
H_2 Leak
Quadrupole
Mass Spectrometer
Sputter

CDHM Sensor

- A thin-walled nickel membrane separates flowing sodium from the high-vacuum region.
- Under dynamic high-vacuum conditions, hydrogen diffuses through the hot liquid sodium and enters the vacuum side through the nickel membrane.
- A high voltage applied in the vacuum region ionizes the diffused hydrogen atoms.
- The Sputter Ion Pump (SIP) measures the resulting ionic current, which is calibrated to determine hydrogen concentration in sodium.
- A Quadrupole Mass Spectrometer (QMS) operates alongside the SIP to further analyze and confirm the hydrogen concentration in sodium.

ECHM Sensor



Electrical lead
Compression fitting
Electrical lead
Knife edged flange
Alumina spacer
Ref. compartment
Ref. electrode
Electrolyte compartment
0.5 mm iron
$CaBr_2$ –CaHBr Electrolyte in iro thimble

Sensor Materials & Internal Structure

- Electrolyte: Solid Ca + $CaBr_2$ mixture → becomes CaHBr + $CaBr_2$ when H_2 passes through.
- Reference Electrode: Biphasic Mixture(Ca, Mg, CaH_2) prepared on SS rod tip.
- Electrolyte placed at base of iron casing; electrode inserted using SS rod.
- 7 aluminium spacers added to prevent rod bending and electrical shorting.

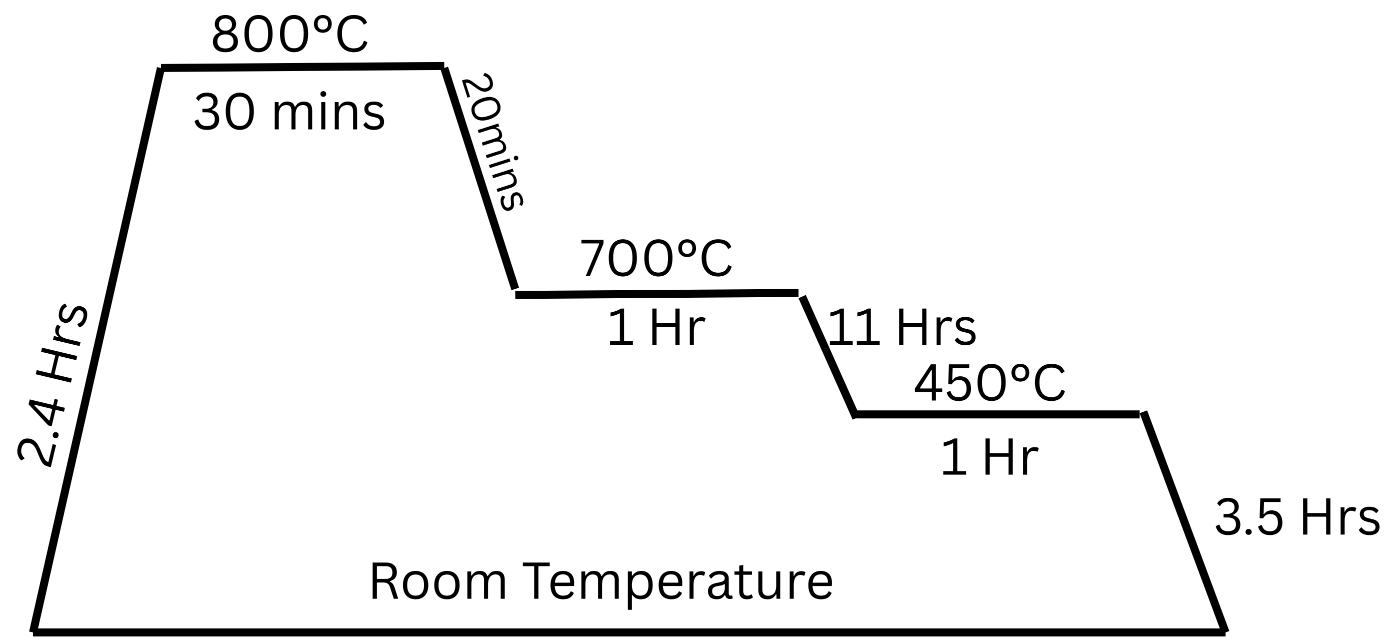
SS: Stainless Steel

Working Principle & Sealing

- H_2 diffuses through 0.5mm Pure Iron, ionizes at electrolyte surface.
- Moves toward Ca/CaH_2 electrode, generating a Nernst voltage proportional to H_2 concentration in sodium.
- Voltage measured between SS rod and casing.
- Casing sealed with Teflon cork + secondary cork to prevent H_2 leakage and ensure long sensor life.
- Electrode must maintain a 5 mm gap from electrolyte base.

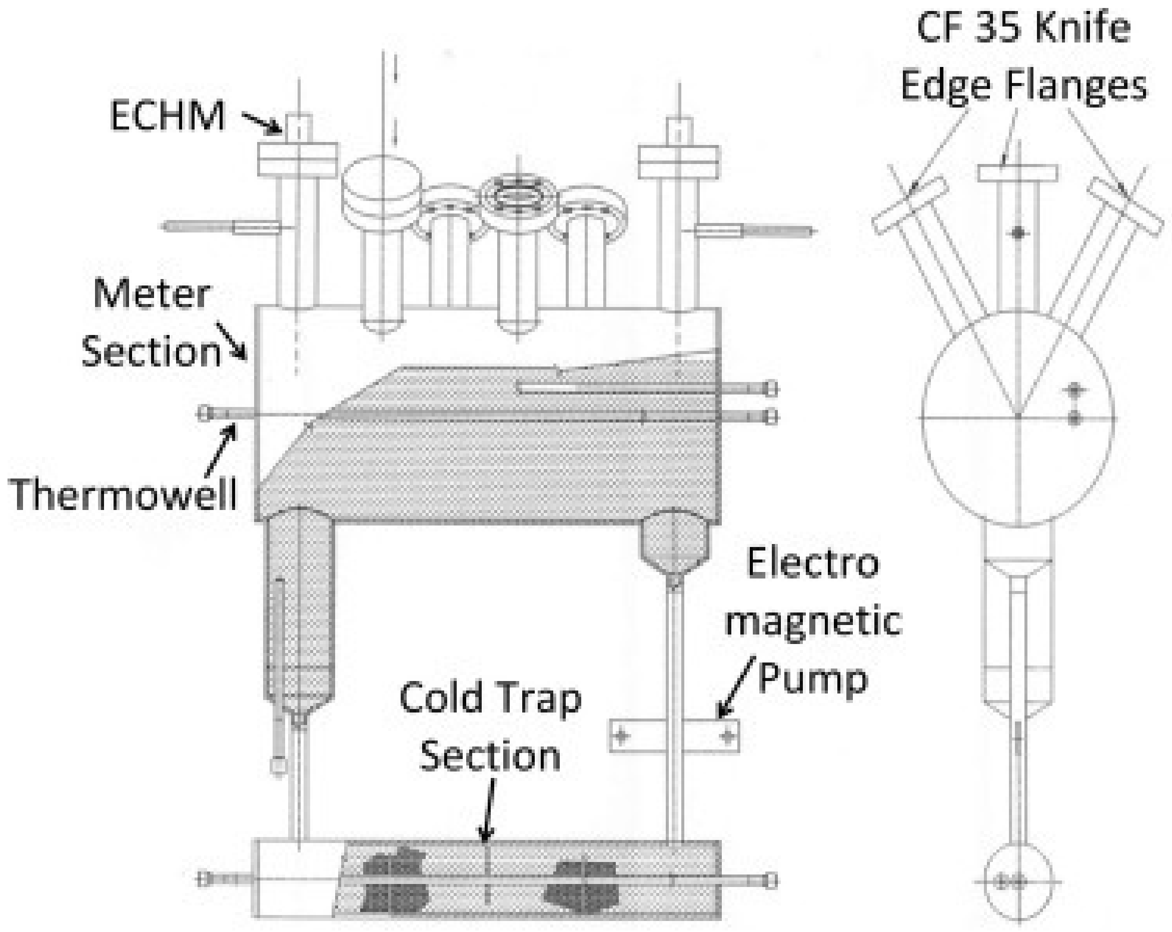
Casting, Cooling & Issues

- Meter heated to 800 °C (2 hrs) to melt electrolyte; SS rod inserted to marked point (maintains 5 mm gap).
- Cooling done gradually for homogeneous electrolyte distribution.
- Manual handling may cause cracks.
- Improper cooling may create voids, affecting calibration & stability.



Sodium Loop

- Total sodium inventory: ~8 kg
- Loop consists of meter section and cold trap, connected by SS tubes
- Meter section has six ports; all sections heated by resistance heaters
- Electromagnetic pump circulates sodium
- Cold trap packed with SS mesh to remove oxides & hydrides
- Thermowells in meter and cold trap; thermocouples monitor temperatures
- ECHM sensors placed in meter section for response measurement



Sensor Response Monitoring

- R + ECHM response tracked during cold trap temperature variations
- Stable EMF recorded at each constant cold trap temperature
- Temperature cycled (heating, cooling, random) for 3 months to ensure reproducibility

ECHM Sensor

Strengths:

- High sensitivity, compact, low maintenance.
- Reliable for >450°C reactor conditions.

Limitations:

- Electrolyte degradation, corrosion, drift over long use.
- Calibration difficult due to temperature-dependent solubility.
- Response time slower than gaseous sensors.

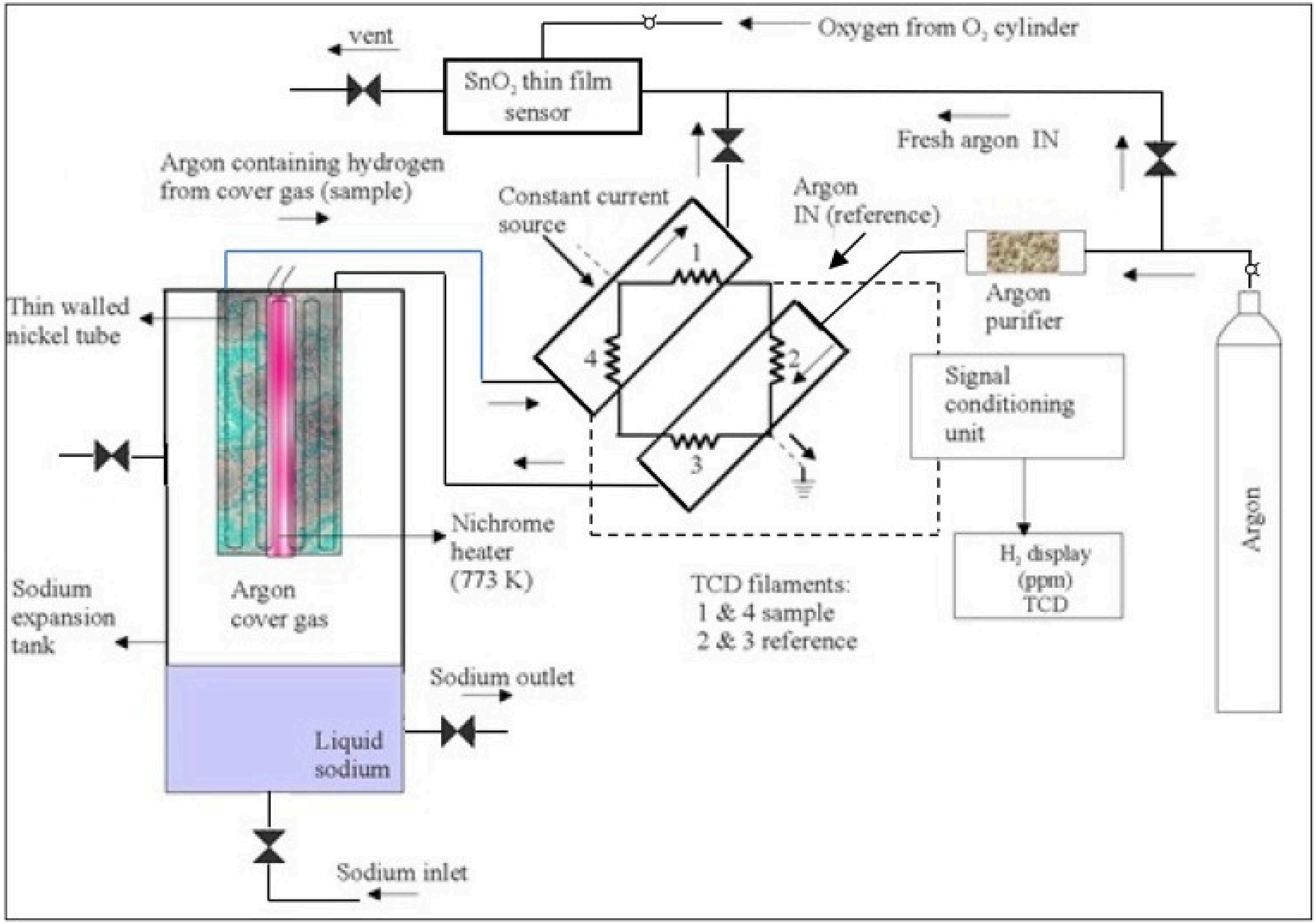
Gaps in Sodium Sensor Tech

- EMF drift & temperature nonlinearity
- Slow sensor dynamics
- Material degradation reducing the lifetime of the sensor
- Formation of cracks in the sensor cause irregular readings

Hydrogen in Argon Detection

- Below 400°C, hydrogen escapes into argon cover gas.
- Thermal Conductivity Detector (TCD) and SnO_2 sensor used.
- TCD measures difference in thermal conductivity between pure Ar and $Ar+H_2$.
- SnO_2 senses hydrogen when surface oxygen ions (O^-) react with H_2 to form H_2O, releasing electrons back into the semiconductor and reducing its resistance.

HAD Implementation



TCD Operation (Carrier & Sample Flow)

- The TCD uses four filaments arranged as a Wheatstone bridge: two for reference gas (argon carrier) and two for sample gas (cover gas).

- Bypass mode:
  - Argon carrier enters the reference side of the TCD.
  - It bypasses the Ni diffuser assembly (component B).
  - It returns to the sample side and exits through the outlet tube into the atmosphere.

- Sample mode:
  - Carrier gas enters the reference side of the TCD.
  - It flows through the Ni diffuser tube, sweeping any dissolved or leaked H_2.
  - It then enters the sample side and is vented out.

- Flow rate: About 30 ml/min of argon flows through the TCD filaments, previously controlled by an MFC.

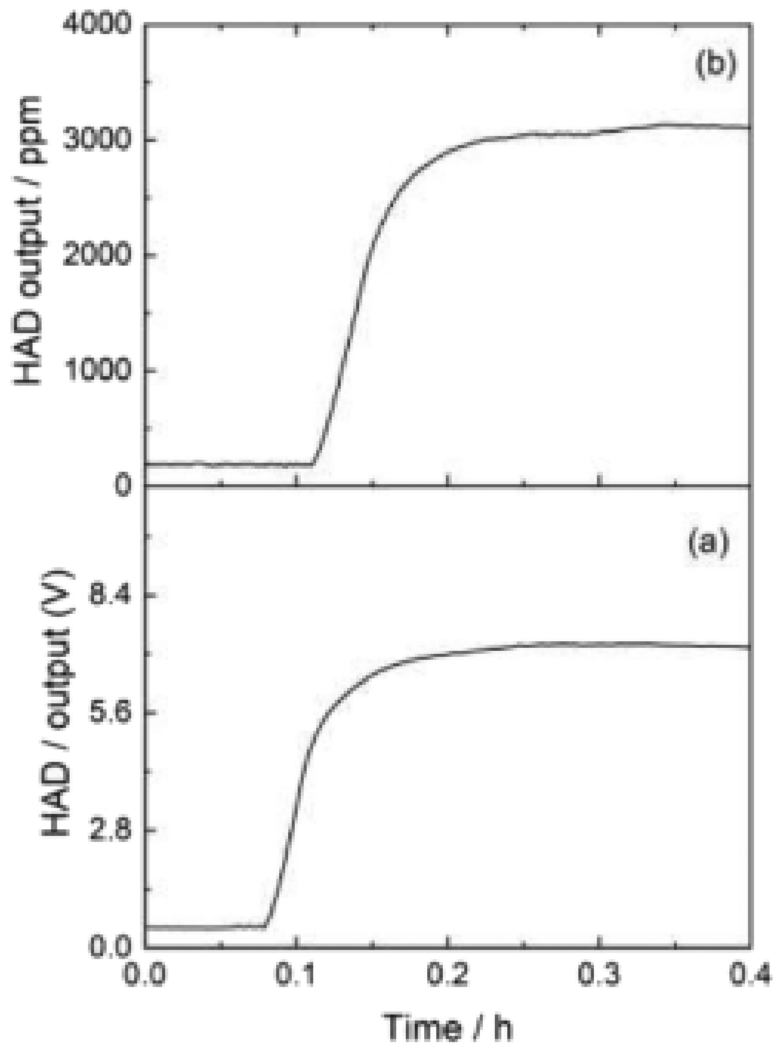


FIG. 7. Typical response of HAD toward (a) 3000 ppm of hydrogen in argon (without ppm factor) and (b) 3000 ppm of hydrogen in argon (with ppm factor) in the cover gas expansion tank for NCA at 773 K.

Range: 30ppm - 3000ppm

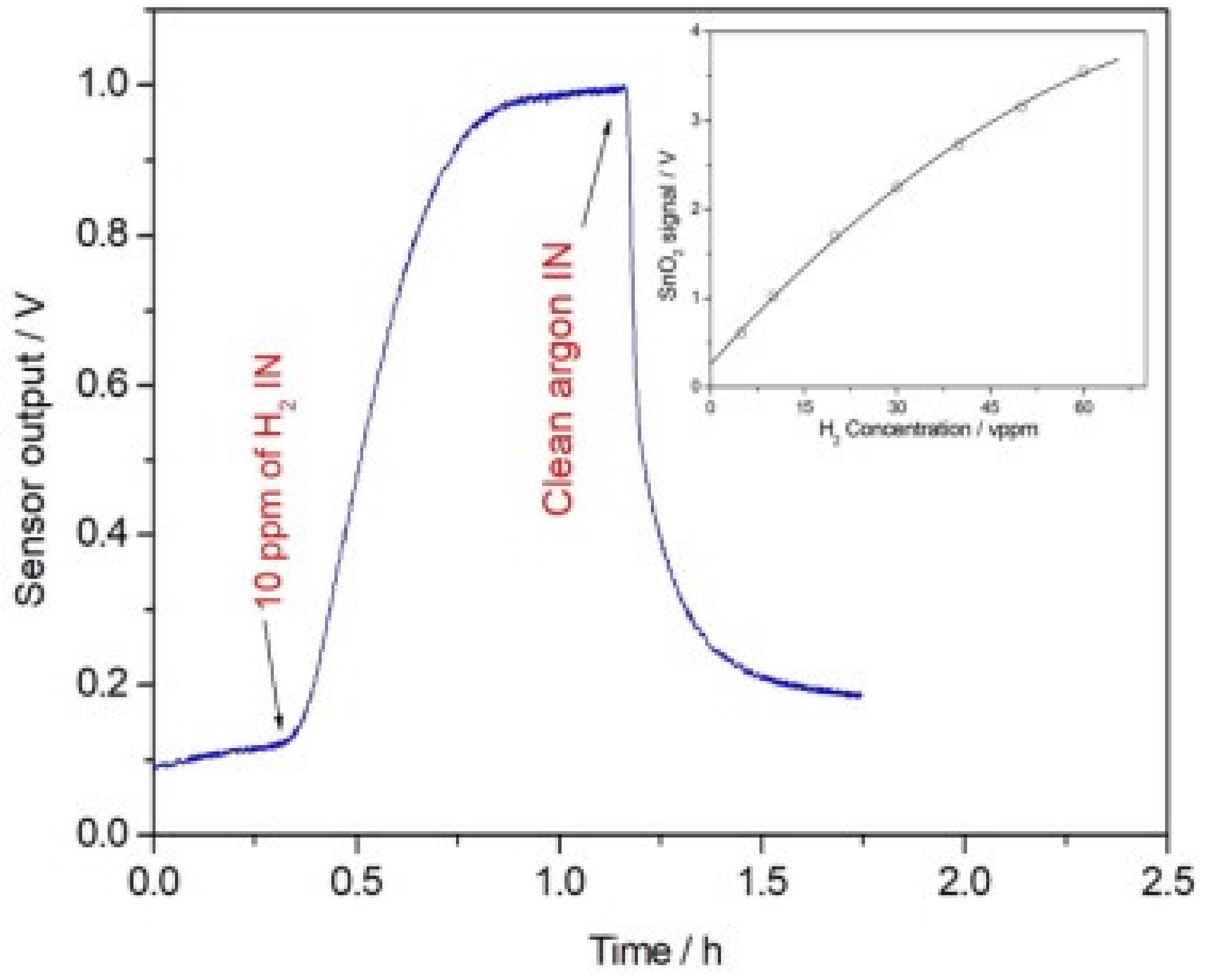
Metal Oxide Sensor Working

Formation of surface oxygen ions

- SnO_2 supplies electrons to the surface:
    - $Sn^{2+} \rightarrow Sn^{4+} + 2e^-$
- Oxygen adsorbs and forms different ions depending on temperature:
    - O^- dominates at intermediate temperatures (≈150–300 °C)
    - O^{2-} dominates at higher temperatures (≥300 °C)
- Example ion-formation step:
    - $O_2 + e^- \rightarrow O^-$

Metal Oxide Sensor Working

Range: 10ppm - 1000ppm



- Reaction of hydrogen with surface oxygen
  - Hydrogen reacts with the adsorbed oxygen ions:
    - $H_2 + O^- \rightarrow H_2O + e^-$
  - (At higher temperatures: $H_2 + O^{2-} \rightarrow H_2O + 2e^-$)

- Effect on sensor signal
  - The reaction releases electrons back into SnO_2,
  - reducing the surface depletion layer,
  - causing a drop in resistance, which is detected as the hydrogen signal.

Insights from HAD Study

- Temperature correction vital to minimize electronic noise.
- Carrier gas flow, pressure, and Ni membrane temperature significantly influence hydrogen diffusion across the nickel coil.
- HAD sensitivity increased with higher Ni temperature (0.72 V/bar at 798 K).
- Stable hydrogen detection requires constant flow, fixed bridge current, and controlled cover-gas pressure, ensuring minimal drift.
- Future improvements focus on improved electronics, better shielding, and advanced signal compensation to further reduce noise and enhance reliability.

Cover Gas Gaps & AI Potential

- Flow-rate & temperature drift
  - Papers show drift from ambient temp & flow sensitivity.
  - AI: Kalman/LSTM filtering for real-time drift correction.
- TCD/Ni membrane stability
  - Filament aging, diffusion efficiency vary with use.
  - AI: Predictive-maintenance models for sensor health.
- Baseline drift
  - Uncorrected HAD noise ±230 mV → ±2.4 mV after correction.
  - AI: Denoising autoencoders for continuous baseline correction.

Effect of Ambient Temperature on MFC & HAD Output

- Liquid sodium temperature in the plant varies between 473–773 K, with higher temperatures during normal operation.
- This causes ambient temperature variation between 300–323 K.
- Ambient temperature changes affect the Mass Flow Controller (MFC) performance.
- Temperature variation introduces thermal noise, disturbing the HAD (Hydrogen-in-Argon Detector) output.

Major Gap Area

- At >400 °C, due to faster reaction kinetics, NaOH and H_2 react quickly with sodium → hydrogen dissolves rapidly → use ECHM/SIP to monitor dissolved H_2.
- At <300 °C, reaction kinetics are slow → hydrogen does not dissolve fully → escapes into argon cover gas → use TCD/SnO_2 to monitor gaseous H_2.
- In the 250–400 °C transition zone, both gaseous and dissolved hydrogen coexist → dual sensor responses (SnO_2/TCD + ECHM/SIP) cause ambiguous or delayed detection.
- No established correlation between hydrogen concentration, electromagnetic impulse, and temperature in this transition region.

AI Usage and Implementation

Signal Interpretation & Noise Reduction

- AI can remove baseline drift caused by temperature, flow-rate changes, and corrosion using LSTM, Gaussian Processes, or Kalman-NN models.
- AI can enhance weak or noisy signals using denoising autoencoders or adaptive filters to reliably detect low-level or transient H_2 events.

Calibration & Compensation

- AI models can learn complex calibration curves (neural nets, SVR - Support Vector Regression), reducing or eliminating frequent manual calibration.
- Physics-informed ML can automatically compensate for variations in temperature, sodium purity, and impurity levels using combined thermodynamics + empirical data.

AI Usage and Implementation

Sensor Health Monitoring & Predictive Maintenance

- AI can detect early electrolyte degradation or electrode poisoning by identifying anomalies in EMF/TCD baseline patterns.
- AI can optimize recalibration intervals using drift trend analysis and reinforcement learning, extending sensor life.

Data Fusion & Virtual Hydrogen Sensing

- AI can fuse data from TCD, ECHM, pressure, and temperature sensors to generate a virtual hydrogen sensor that remains stable even when one sensor drifts.
- Hybrid physics + ML can estimate real-time hydrogen concentration even with sparse, slow, or delayed CDHM measurements.

AI Usage and Implementation

Anomaly & Leak Detection

- Time-series AI can detect rapid Na–H_2O reaction leaks by identifying sudden deviations in EMF, sodium temperature, or pressure.
- High-frequency pattern detection can detect tiny hydrogen ingress events below manual threshold limits.

Design & Optimization

- AI-driven materials search can identify corrosion-resistant electrolytes and durable electrode materials for future ECHM/TCD sensors.
- AI-assisted CFD surrogate models can optimize sensor geometry and flow paths, improving response time, sensitivity, and long-term stability.

Hydrogen Management System

A centralized web-based platform for real-time hydrogen monitoring and safety.

- Continuously tracks hydrogen levels from sensors installed in critical areas
- Provides instant visibility through a simple, user-friendly web dashboard
- Sends alerts during abnormal hydrogen buildup to support quick decision-making
- Enhances plant safety, reduces manual monitoring, and ensures early detection of hazards
- Scalable solution that can integrate multiple sensors and multiple plant zones

Expected Outcomes

- Reliable multi-environment hydrogen monitoring method.
- Established relation between temperature, Hydrogen conc. and Electrical Impulse at temperatures 250 °C – 400 °C
- Improved accuracy, stability, and detection limits (<30 ppm).
- AI-assisted calibration and drift correction.
- Framework for fail-safe sodium reactor health monitoring.

Integrated Methodology & Future Scope

- Combine sodium (ECHM) and argon (HAD/TCD) sensor data for holistic leak detection.
- Use sensor fusion models to correlate H_2 dynamics across phases.
- Develop AI-driven signal correction and digital twin simulation for predictive safety.
- Create a “Hydrogen Health Index” indicating reactor leak likelihood in real time.

THANK YOU