Meet the Presenter

Dr. Sam Suppiah is currently the manager of the Chemical Engineering Branch and the Facility Authority for Tritium Facility Operations at the Canadian Nuclear Laboratories (CNL), Chalk River, Ontario. He earned his chemical engineering degree and PhD from the University of Birmingham, UK, and worked for a contracting company and British Gas Corporation in the UK before joining AECL (now CNL). He is a Professional Engineer in Ontario, and a certified Project Management Professional (PMP). He has more than 35 years of expertise in the areas of Heavy Water and Tritium, Catalysis, Electrolysis Technologies, Fuel Cell Technologies, Nuclear and non-Nuclear Battery Technologies, Hydrogen Production from High and Medium Temperature Thermochemical Processes, Steam Electrolysis and Energy Storage. His current focus at CNL in the area of hydrogen production is in the development of the hybrid copper-chlorine cycle. This development is approaching lab-scale continuous operation demonstration in 2021. Dr. Suppiah has been leading collaborations in many of the above areas with industry, institutes and universities. He is the Canadian delegate for and the current Chair of the GEN IV VHTR Hydrogen Production Project Management Board. He is also a board member of the Canadian Hydrogen and Fuel Cell Association (CHFCA). He has been a regular presenter at IAEA’s technical meetings and other national and international meetings on hydrogen production.

Email: sam.suppiah@cnl.ca
Presentation Outline

- Overview of Hydrogen PMB
  - Historical
  - Members
  - Responsibilities

- Hydrogen Technologies
  - Current
    - Fossil based
    - 100% electrical based
  - Thermochemical & High Temperature Steam Electrolysis

- Current & Future Developments in Hydrogen Production by Member States

- Summary
GIF Governance Structure

*The Technical Director is Chair of the Experts Group
# Overview of VHTR HP PMB

<table>
<thead>
<tr>
<th>Name</th>
<th>First Name</th>
<th>Function</th>
<th>Email</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPPIAH</td>
<td>Sam</td>
<td>Chair</td>
<td><a href="mailto:sam.suppiah@cnl.ca">sam.suppiah@cnl.ca</a></td>
</tr>
<tr>
<td>LEE</td>
<td>Tae Hoon</td>
<td>Co-chair</td>
<td><a href="mailto:leeth@kaeri.re.kr">leeth@kaeri.re.kr</a></td>
</tr>
<tr>
<td>DOMINGUEZ</td>
<td>Maria-Theresa</td>
<td>Member</td>
<td><a href="mailto:mdb@empre.es">mdb@empre.es</a></td>
</tr>
<tr>
<td>TAKEGAMI</td>
<td>Hiroaki</td>
<td>Member</td>
<td><a href="mailto:takegami.hiroaki@jaea.go.jp">takegami.hiroaki@jaea.go.jp</a></td>
</tr>
<tr>
<td>SARRADE</td>
<td>Stephane</td>
<td>Member</td>
<td><a href="mailto:stephane.sarrade@cea.fr">stephane.sarrade@cea.fr</a></td>
</tr>
<tr>
<td>O’BRIEN</td>
<td>Jim</td>
<td>Member</td>
<td><a href="mailto:james.obrien@inl.gov">james.obrien@inl.gov</a></td>
</tr>
<tr>
<td>LE NAOUR</td>
<td>François</td>
<td>Substitute</td>
<td><a href="mailto:francois.le-naour@cea.fr">francois.le-naour@cea.fr</a></td>
</tr>
<tr>
<td>ROEB</td>
<td>Martin</td>
<td>Substitute</td>
<td><a href="mailto:martin.roeb@dlr.de">martin.roeb@dlr.de</a></td>
</tr>
<tr>
<td>MYAGMARJAV</td>
<td>Odtsseg</td>
<td>Substitute</td>
<td><a href="mailto:odtsseg.myagmarjav@jaea.go.jp">odtsseg.myagmarjav@jaea.go.jp</a></td>
</tr>
<tr>
<td>ZHANG</td>
<td>Ping</td>
<td>Observer</td>
<td><a href="mailto:zhangping77@mail.tsinghua.edu.cn">zhangping77@mail.tsinghua.edu.cn</a></td>
</tr>
<tr>
<td>CHANG</td>
<td>Sunyoung</td>
<td>Technical Secretary</td>
<td><a href="mailto:sunyoung.chang@oecd-nea.org">sunyoung.chang@oecd-nea.org</a></td>
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PMB Members (as of March 2020)
### PMB Meetings & Chairmanship History

<table>
<thead>
<tr>
<th>No.</th>
<th>Date</th>
<th>Location</th>
<th>Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26-28 Mar., 2008</td>
<td>San Diego (USA)</td>
<td>INL</td>
</tr>
<tr>
<td>2</td>
<td>23-24 Oct., 2008</td>
<td>Madrid (Spain)</td>
<td>JRC</td>
</tr>
<tr>
<td>3</td>
<td>16-17 April, 2009</td>
<td>Chicago (USA)</td>
<td>INL</td>
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<tr>
<td>4</td>
<td>7-8 Sep., 2009</td>
<td>NEA (France)</td>
<td>NEA</td>
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<tr>
<td>5</td>
<td>21-22 April 2010</td>
<td>Potchefstroom (RSA)</td>
<td>RSA</td>
</tr>
<tr>
<td>6</td>
<td>13-15 Sep., 2010</td>
<td>Daejeon (Korea)</td>
<td>KAERI</td>
</tr>
<tr>
<td>7</td>
<td>14-16 June, 2011</td>
<td>Ontario (Canada)</td>
<td>CNL</td>
</tr>
<tr>
<td>8</td>
<td>21-23 Sep., 2011</td>
<td>Beijing (China)</td>
<td>INET</td>
</tr>
<tr>
<td>9</td>
<td>31 May-1 June, 2012</td>
<td>CNL (China)</td>
<td>CNL</td>
</tr>
<tr>
<td>10</td>
<td>25-26 Oct., 2012</td>
<td>Oarai (Japan)</td>
<td>JAEA</td>
</tr>
<tr>
<td>11</td>
<td>11-12 Apr., 2013</td>
<td>Daejeon (Korea)</td>
<td>KAERI</td>
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<tr>
<td>12</td>
<td>23-24 Sep., 2013</td>
<td>Beijing (China)</td>
<td>INET</td>
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<tr>
<td>13</td>
<td>11-12 Mar., 2014</td>
<td>Grenoble (France)</td>
<td>CEA</td>
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<tr>
<td>14</td>
<td>3-4 Dec., 2014</td>
<td>Beijing (China)</td>
<td>INET</td>
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<tr>
<td>15</td>
<td>3-4 Oct., 2016</td>
<td>CNL (Canada)</td>
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<td>16</td>
<td>17-19 Oct., 2017</td>
<td>Julich (Germany)</td>
<td>JRC</td>
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<td>17</td>
<td>18-19 July, 2018</td>
<td>JAEA (Japan)</td>
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<td>18</td>
<td>7-8 Nov., 2018</td>
<td>Seoul (Korea)</td>
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<td>19</td>
<td>15-17 May, 2019</td>
<td>Grenoble (France)</td>
<td>CEA</td>
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<tr>
<td>20</td>
<td>20-21 Nov. 2019</td>
<td>Shanghai (China)</td>
<td>INET</td>
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<table>
<thead>
<tr>
<th>Meeting No.</th>
<th>Chair</th>
<th>Co-Chair</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Carl Sink (USA)</td>
<td>Nariaki Sakaba (Japan)</td>
</tr>
<tr>
<td>4</td>
<td>Carl Sink (USA)</td>
<td>Pascal Yvon (France)</td>
</tr>
<tr>
<td>5-8</td>
<td>Sam Suppiah (Canada)</td>
<td>Young-Joon Shin (Korea)</td>
</tr>
<tr>
<td>9-12</td>
<td>Young-Joon Shin (Korea)</td>
<td>Sam Suppiah (Canada)</td>
</tr>
<tr>
<td>13-14</td>
<td>Francois Le Naour (France)</td>
<td>Sam Suppiah (Canada)</td>
</tr>
<tr>
<td>15-</td>
<td>Sam Suppiah (Canada)</td>
<td>Tae Hoon Lee (Korea)</td>
</tr>
</tbody>
</table>
The VHTR hydrogen production program aims at developing and optimizing high temperature thermochemical and electrolysis water splitting processes, as well as defining and validating technologies for coupling any Gen IV Nuclear Reactor system to such process plants safely and securely through an international collaborative program.

## VHTR R&D Project

**Hydrogen Production Project Plan**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 March 2008</td>
<td>All of the VHTR HP PA signatories signed the VHTR HP PA for a period of ten (10 years).</td>
</tr>
<tr>
<td>5-6 November 2012</td>
<td>The SSC approved the accession to the PA of INET.</td>
</tr>
<tr>
<td>19 March 2018</td>
<td>The VHTR HP PA was extended for an additional period of ten (10) years until 19 March 2028 as long as the VHTR SA remains in effect.</td>
</tr>
<tr>
<td>Being processed</td>
<td>The PMB finalized the updated project plan adding INET’s contribution.</td>
</tr>
<tr>
<td>To be processed</td>
<td>The SSC approved the updated project plan adding INET’s contribution.</td>
</tr>
<tr>
<td>To be processed</td>
<td>The PA amended by adding INET as a new Signatory.</td>
</tr>
</tbody>
</table>
Hydrogen – A Critical Energy Carrier For Future

Specific Energy

Energy Density: KWH per Gallon

Source: DOE, Green Econometrics research
Current & Future Demand & Use of Hydrogen

Global annual demand for hydrogen since 1975

Transportation:
- Heavy vehicles
- Trains
- Ships
- Aviation

Current Hydrogen Production

- **Fossil source**
  - Steam Methane Reforming
  - Partial oxidation
  - Biomass
  - Others

- **Non-fossil energy source**
  - Advanced Alkaline Electrolysis
  - PEM Electrolysis
Why High Temperature Processes?

Thermodynamics of Thermal Water Splitting - Motivation for High Temperature Processes

$$\begin{align*}
\text{H}_2\text{O} & \longrightarrow \text{H}_2 + 1/2\text{O}_2 \\
1^{\text{st}} \text{ Law: } & Q_H - Q_L = \Delta H_R \\
2^{\text{nd}} \text{ Law: } & \Delta S_R \geq \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \\
\text{Define Process Efficiency: } & \eta_T = \frac{\Delta H_R}{Q_H} \\
\text{Combine } 1^{\text{st}} \text{ and } 2^{\text{nd}} \text{ Laws: } & \eta_{T, \text{max}} = \frac{1 - T_L / T_H}{1 - T_L \Delta S_R / \Delta H_R} \\
\end{align*}$$

If $T = T_L = T_0$ and $P = P_0$ and the H$_2$O enters as a liquid,

$$\eta_T = \left(1 - \frac{T_L}{T_H}\right) \left(\frac{HHV}{-\Delta G^\circ_{f, H_2O}}\right) = \left(1 - \frac{T_L}{T_H}\right) \frac{1}{.83}$$

Maximum possible efficiency

$\eta_{\text{min}} = .65$ of maximum
Hydrogen from GEN IV Nuclear Technologies

Sulphur-Iodine Process

Copper-Chlorine Process

High Temperature Steam Electrolysis

Hybrid-Sulfur Process
Development of the Sulfur-Iodine Cycle:

- Process evaluation including flowsheet optimization, selection of construction materials with suitable corrosion and mechanical properties and selection of catalysts for SO$_3$ and HI decomposition.
- Bench-scale experiments to optimize process conditions.
- Pilot-scale plant construction and performance testing to confirm scaling parameters and materials performance.
- Long-term testing for validating catalyst performance and suitability of construction materials.
H₂ Production PMB Goals and Objectives (cont.)

Development of High Temperature Steam Electrolysis:

- Process evaluation including flow sheet optimization and development of methods for separation of hydrogen from the residual steam.
- Development of advanced materials for electrodes, electrolytes and interconnections, particularly for achievement of low cell and stack resistance and for decreased degradation rates.
- Development of advanced cell and stack designs.
- Experimental testing of promising cell configurations and materials at scales ranging from watts to multi-kW, and in pressurized stack experiments.
- Pilot-scale plant (200 kW) construction and demonstration.
- Theoretical and experimental feasibility studies of high-temperature co-electrolysis of steam and CO₂ while integrating different primary energy sources.
Development of Copper-Chlorine (Cu-Cl) Cycle and Assessment of other alternative cycles and economic evaluation

- Cu-Cl Cycle evaluation including determination of process options, flow-sheet optimization and selection of materials.
- Cu-Cl Cycle component and bench-scale experiments to define and evaluate key parameters such as thermodynamic properties, rate constants, and equipment selection.
- Integrated testing of lab-scale system for 100 L/h hydrogen production.
- Development of HyS process: SO₂ Depolarization Electrolyser (SDE) development, and laboratory-scale tests and optimization.
- Technical evaluation of potential alternative cycles with reference to S/I and HTSE regarding methodology, feasibility and process efficiency and economics.
- Basic R&D as proof of principle for process development.
- Economic evaluation for all hydrogen production processes coupled to nuclear reactors.
Hydrogen Production and Nuclear Reactor Coupling

- System evaluation and optimization of coupling circuits.
- Develop standards on the separation of nuclear reactor and hydrogen production process.
- Develop methodology and requirements for all safety aspects.
- Develop methodology for system integration.
Schematic of the Sulfur-Iodine Process
JAEA Progress on Sulfur-Iodine Process R&D

H₂ production test facility (~ 0.1 Nm³/h scale)

Industrial material component test 2010~

R&D on elemental technologies 2005~2009

Bench-scale test 1999~2004
- 1-week continuous H₂ production by glass apparatus (0.03 Nm³/h-H₂)

Lab-scale test ~1997

HTTR-GT/H₂ test

Commercial use
Technology transfer to private company

Establishment of base technology

HTTR
H₂ facility
Helium gas turbine power generation
JAEA Time-line on H₂ Production Developments Using Sulfur-Iodine Process

- **Continuous H₂ production integrated 3 sections**
  - Date: October 2016
  - Rate: 20 L/h
  - Operation time: 31 hours
    - The developed HIx solution transport technology was confirmed.
    - The technology to prevent I₂ precipitation in HI decomposition section was confirmed.

- **Long-term continuous H₂ production**
  - Date: January 2019
  - Rate: 30 L/h
  - Operation time: 150 hours
    - 150 hours: Solution in three HI sections was circulated 3 times.
    - Improved glass lined sheath functioned well during operation.

- **Current Status**
  - The facility is under overhaul inspection to acquire long-term corrosion data after long-term H₂ production test.
  - Higher H₂ production tests are planned to acquire a set of data with a range varying composition, and development of an automatic control system.

*https://www.jaea.go.jp/02/press2018/p19012502/
Japanese Scenario for HTGR Hydrogen Production System

The first of HTGR commercial system will be available in 2040, considering technological advancements and demand growth of H2.

**HTGR cogeneration system for hydrogen and electricity**

<table>
<thead>
<tr>
<th>Reactor thermal power</th>
<th>600 MWt</th>
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<tbody>
<tr>
<td>Power generation</td>
<td>87 MWe</td>
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<tr>
<td>Hydrogen production rate</td>
<td>70,000 Nm³/h (6.2 ton/h)</td>
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</table>

**Site location**

**Domestic**

Installation in sites of existing nuclear power plant

**Overseas**

Installation in developing nations as hydrogen supplier

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Japanese R&D Progress

- Development of chemical reactor technology with contributions from industrial materials.
- Entire process, with all three sections integrated, was operated for 31 hours at a hydrogen production rate of 20 L/h in Oct. 2016, and was extended to 150 hours at a hydrogen production rate of 30 L/h.
- Currently, an overhaul inspection task to investigate long-term corrosion impacts of all component materials is underway.
- HTGR hydrogen production system will be available from 2040 onwards to meet the growth of hydrogen demand.
**INET’s Efforts for a Low-Carbon Economy (China)**

### Nuclear hydrogen program at INET

- **Iodine sulfur (IS) process**: high efficiency, CO2 free, large-scale hydrogen production technology.
- **High temperature steam electrolysis (HTSE)**: high efficiency, modular design, flexible and suitable to various scale H2 production.
- R&D on the two processes were conducted in parallel since 2005, and IS process was selected for scaling up and potential coupling to HTR-10.

### R&D route of NH through IS process

- **Key tech. process**
- **Simulation and continuous operation**
- **Key components**
- **Engineering materials**
- **Coupling tech.**
- **Scaling-up safety**

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<td>System integration</td>
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<td>Key components</td>
<td></td>
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<td>Pilot demo</td>
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P. Zhang, et al. *Renewable & Sustainable Energy Reviews*, [https://doi.org/10.1016/j.rser.2017.05.275](https://doi.org/10.1016/j.rser.2017.05.275)
Current & Future R&D Activities in China

- Development of the key reactor components
  - Sulfuric acid decomposer
  - HI decomposer
  - Bunsen reactor
  - EED

- Dynamic simulation

- Pilot scale IS development (two phases, ~10 years)
  - Safety issues on nuclear hydrogen
  - Key technologies of pilot scale
    - Engineering materials
    - Reactors, components, loops……
  - HTR-IS coupling technology (2021-2025)
    - Scale-up of components
    - Coupling technology

- HTR technology for H2 production and heat application
  - VHTR (950-1000°C)
  - IHX
Some Operational Results from Longest Test Conducted at INET

H$_2$SO$_4$ Decomposer Catalyst tests
Update of Korean H$_2$ Related R&D Status

- Earlier focus on Sulphur-Iodine process developments
- Hydrogen Production Process coupled to the HTGR
- 350 MWth Cogeneration PFD with HTSE process
HTSE Leverages Fuel Cell Technology

There are fundamental differences between SOFC and SOEC modes of operation:

- Direction of mass fluxes
- Heat requirement / rejection
- Performance degradation / lifetime is worse in electrolysis than in fuel cell mode
Carbon Free HYDROGEN Production

SOEC : High Temperature Electrolyser, the competitive solution

In 10 years of R&D:

- Performance improvement: X8
- Lifetime: > 2500 hours
- Number of cells/stack: x 25
- 1st prototype of integrated system
- Demonstrated yield at system level: 87% PCI
- Cost reduction of stack: -80%
- Background patent portfolio: 40 patent family on stack

Bonus: Reversible Technology
Specific Developments on Module & Systems
CEA projects in progress

- 2014: 1st 5 kWe HTSE system started at CEA
  - 1 stack – 1 Nm3/h of H2
  - Electrical efficiency - 99% HHV
  - Atmospheric pressure
  - Temperature of electrolyze: 700°C

- 2018: 1st reversible system delivered to an industrial (ENGIE)
  - 1 stack – 1 Nm3/h of H2 production, 1 kWe in fuel cell mode
  - Electrical efficiency – 84% in electrolyze mode, 55% in fuel cell mode
  - Time to switch: 15 minutes

- 2020: Multimodules multistacks reversible system to be delivered in Italy
  - 20 kWe in E-mode
  - 16 Nm3/h of H2 production in E-mode
  - 15 kWe in FC-mode

- 2019-2022: Grinhy 2.0 Project
  - 720 kWe in E-mode
  - Target -100t H2 of production within 2022
Carbon Free H₂ Production

Experimental results - 6kW experimental scale

- Waste heat can be used for steam generation at 150°C
- In addition, the heat from outlet gas can be recovered thanks to high-efficiency heat exchangers (exothermic operation point)
- A 90% HHV electrolysis efficiency is measured at the system level
Advanced HTSE to Further Reduce the Cost of Hydrogen Production

Rated electrical Power – 6 kW
Load variation – 0% - 100%
Electrical efficiency (HHV) – 85%
Specific electric Power – 3.5 kWh/Nm3
H2 Production – 2 Nm3/h
H2 pressure – 3 bar

Cost of producing hydrogen in 2030 between 1 and 1,5 €/kg
US Advanced Hydrogen Production Research & Current Efforts for a Low-Carbon Economy

Energy Systems Laboratory
Systems Integration Lab

Focused on Nuclear Hybrid Energy Systems Concept & Dynamic Energy Transport & Integration Laboratory
Accomplishments and Progress

Advance the state of the art of High Temperature Electrolysis (HTE) technology while demonstrating grid and thermal energy integration and dynamic performance characteristics

- **Completed Design and Installation of Facility Support Infrastructure**
  - Power, DI water system, drain lift station, enclosure, ventilation system, H2 vent, gas monitoring, safety interlocks, fire protection, structural support systems
- **Completed Design and Installation of 25 KW HTE Test Facility**
  - Steam generation and supply system
  - High-temperature furnace
  - High-temperature air supply for sweep gas
  - N2 purge systems
  - Hydrogen recycle and gas dryer system
  - Gas monitoring system with interlocks
  - Instrumentation
- **Initial testing is currently underway**
- Facility has been commissioned for HTE hydrogen production up to the 25 kW scale
- Initial testing at the 5 kW scale is under way
US Activities in HTSE Development Over the Last Decade

Cell and Stack Designs Studied By INL

- Externally manifolded planar stack, electrolyte-supported cells (Ceramatec)
- Internally manifolded cross-flow planar stack with anode-supported cells (MSRI, Versa Power)
- Internally manifolded counter-flow planar stack with anode-supported cells (St. Gobain/FZ Julich)

Integrated planar (segmented-in-series) stack, ceramic substrate-supported cells (Rolls Royce)
Subcontractor Testing

MSRI

- Small R&D company located in Salt Lake City
- Developer of planar SOFCs and other electrochemical technologies for power and hydrogen production
- INL subcontractor for SOEC development and testing

5-cell SOEC stack installed in test stand at MSRI

Individual cell voltages, long-term SOEC test, demonstrated <2.5% /khr degradation over 1200 hours
EU Development of HTSE Using Solar Power

Solar hydrogen production at 6.75 L/min
Hybrid Cu-Cl Thermochemical Hydrogen Production
Attractiveness of Cu-Cl Cycle

- High efficiency and better economics at large scales
- Low temperature requirement for heat source <530°C
- Ideally suited for coupling with Heat Sources-CSP, Small Modular Reactors
- Materials-of-construction and corrosion issues more manageable at 530°C than at higher temperatures required by other cycles
- Inexpensive raw materials as recycle agents (for example, compared to iodine for S-I cycles)
- No requirement for catalyst in thermal reactions

However there is a requirement for solid handling!!
Simplified Integrated Cu-Cl Cycle Concept

Figure: A schematic of the Copper-Chlorine Cycle for hydrogen production
Step 1: Electrolysis Step Development

Originally considered to be the most difficult

Process Diagram of the Electrolysis Experimental System

2CuCl(s) + 2HCl(aq) → 2CuCl₂(s) + H₂(g)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target Value</th>
<th>Actual Experimental Value</th>
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</thead>
<tbody>
<tr>
<td>Hydrogen Production</td>
<td>50 L/h</td>
<td>50 L·h⁻¹</td>
</tr>
<tr>
<td>Cell Electrode Area</td>
<td>100 cm²</td>
<td>Three 100 cm² in series</td>
</tr>
<tr>
<td>HCl Concentration</td>
<td>6.0-8.0 M</td>
<td>8.0 M</td>
</tr>
<tr>
<td>Initial CuCl Concentration</td>
<td>0.5-2.0 M</td>
<td>2.0 M</td>
</tr>
<tr>
<td>Temperature</td>
<td>70-80 °C</td>
<td>80 °C</td>
</tr>
<tr>
<td>Liquid Flow</td>
<td>0.2 L·min⁻¹</td>
<td>0.2 L·min⁻¹</td>
</tr>
<tr>
<td>Current Density</td>
<td>0.4 A·cm⁻²</td>
<td>0.4 A·cm⁻²</td>
</tr>
<tr>
<td>Extent of Reaction</td>
<td>50-80%</td>
<td>Up to 75%</td>
</tr>
<tr>
<td>Pressure</td>
<td>&lt;103.4 kPa</td>
<td>Anode: &lt;6.9 kPa; Cathode: &lt;34.5 kPa</td>
</tr>
</tbody>
</table>
Step 2: CuCl/CuCl\textsubscript{2}/H\textsubscript{2}O/HCl Separation System

CuCl\textsubscript{2}(aq) → CuCl\textsubscript{2}(s)
Step 3: Experimental Study of CuCl$_2$ Hydrolysis

2CuCl$_2$(s) + H$_2$O(g) → Cu$_2$OCl$_2$(s) + 2HCl(g)

Step 4: \( \text{Cu}_2\text{OCl}_2 \) Decomposition

\[
\text{Cu}_2\text{OCl}_2(s) \rightarrow 2\text{CuCl}(l) + \frac{1}{2}\text{O}_2(g)
\]
Lab-scale Demonstration Plan

Pilot plant demonstration
- Pilot plant design
  - 1 tonne/day $\text{H}_2$
- Integrated lab-scale
  - 100 g/day $\text{H}_2$

<table>
<thead>
<tr>
<th>Laboratory Process Development</th>
<th>Pilot Plant Design</th>
<th>Pilot Plant Demonstration</th>
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<td>2018-2021</td>
<td>2022-2023</td>
<td>2024-2026</td>
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- Application Study Collaborations
- Commercial Partners
- CNL-Govt-Private Investment

Location, Energy Sources, H2 Customer
Development of this technology has been limited:

- In the early part of the first ten-year Project Arrangement of the Hydrogen PMB (around 2008), there was considerable interest on this technology in the US.
- Some EU institutions have resumed development of this cycle for solar energy applications.
- Currently, INET (China) is also starting experimental work on the development of the electrolyser used in the cycle.
Summary

- Good progress is demonstrated by the member countries
  - Operation of integrated Sulfur-Iodine process has been demonstrated
    - However, materials related issues require resolution for industrial demonstration
  - High temperature steam electrolysis technology has reached mature state
    - Degradation of cell components requires continuing advances
  - Copper-Chlorine cycle development is approaching lab-scale demonstration
    - Operation of integrated system requires solid transfer issues resolved

- All the above hydrogen production processes still require demonstration of economical production capabilities
  - With advances through the planned developments, it is believed that economical hydrogen production can be achieved with these processes
Upcoming Webinars

28 May 2020  Performance Assessments for Fuels and Materials for Advanced Nuclear Reactors  Prof. Daniel LaBrier, ISU, USA

24 June 2020  Comparison of 16 Reactors Neutronic Performance in Closed Th-U and U-Pu Cycles  Dr. Jiri Krepel, PSI, Switzerland

29 July 2020  Overview of Small Modular Reactor Technology Development  Dr. Frederik Reitsma, IAEA