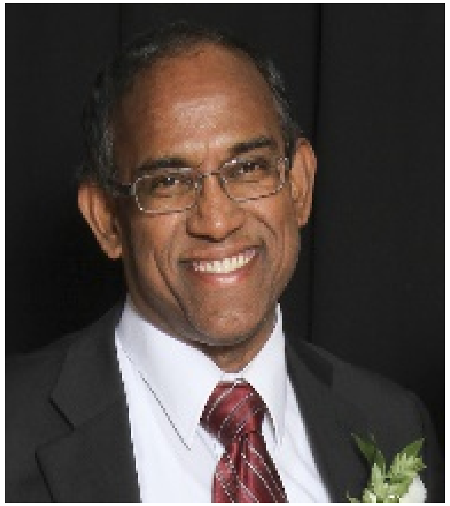
GEN IV International Forum℠

GIF VHTR HYDROGEN PRODUCTION PROJECT MANAGEMENT BOARD

Dr. Sam Suppiah
CNL, Canada
29 April 2020

Meet the Presenter



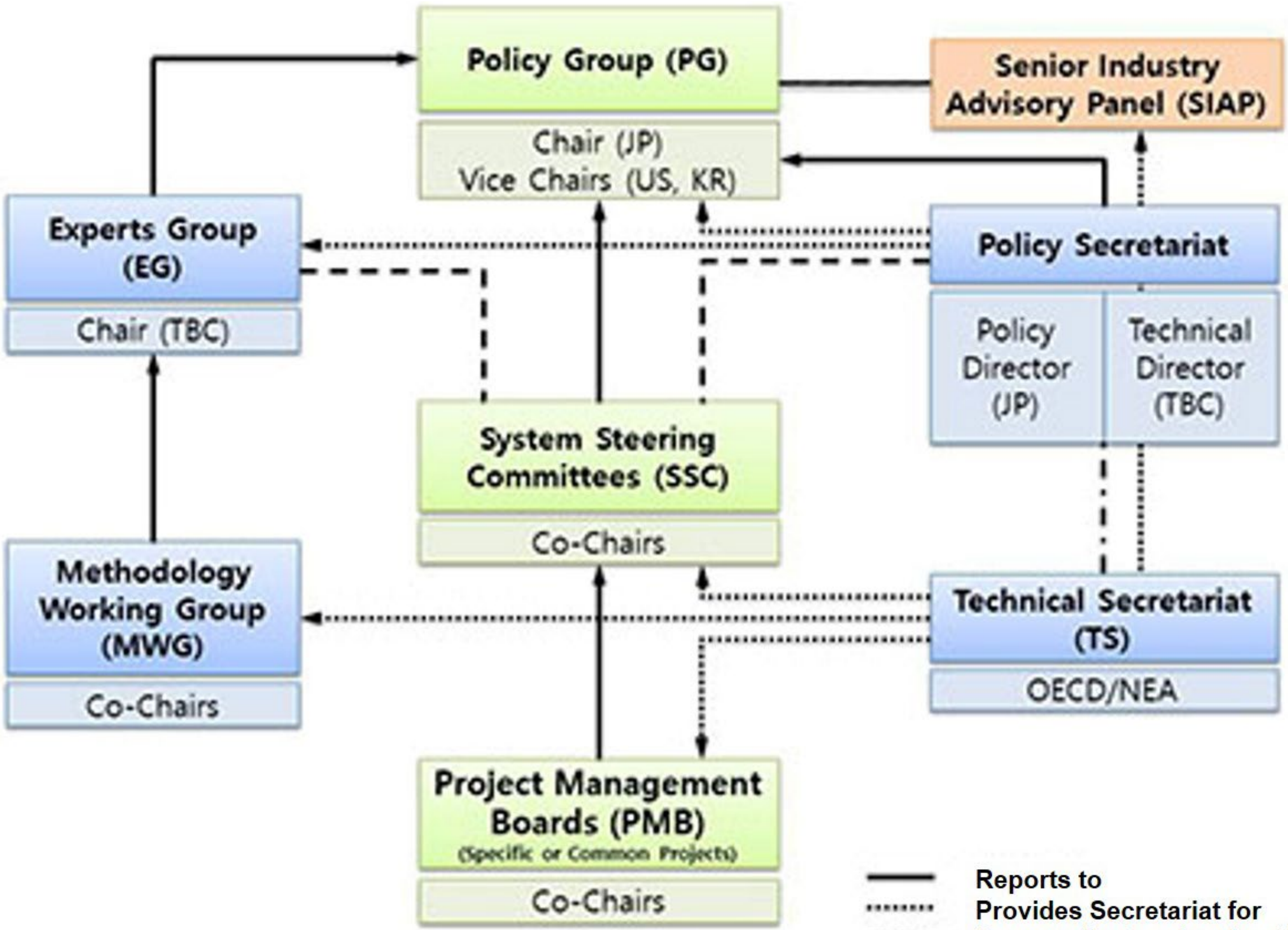
Dr. Sam Suppiah is currently the manager of the Chemical Engineering Branch and the Facility Authority for Tritium Facility Operations at the Canadian Nuclear Laboratories (CNL), Chalk River, Ontario. He earned his chemical engineering degree and PhD from the University of Birmingham, UK, and worked 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



Policy Group (PG)
Chair (JP)
Vice Chairs (US, KR)

Senior Industry Advisory Panel (SIAP)

Experts Group (EG)
Chair (TBC)

Policy Secretariat
Policy Director (JP)
Technical Director (TBC)

System Steering Committees (SSC)
Co-Chairs

Methodology Working Group (MWG)
Co-Chairs

Technical Secretariat (TS)
OECD/NEA

Project Management Boards (PMB)
(Specific or Common Projects)
Co-Chairs

—— Reports to
⋯⋯ Provides Secretariat for
– – – Communicates closely with
– · – Coordinates with

*The Technical Director is Chair of the Experts Group

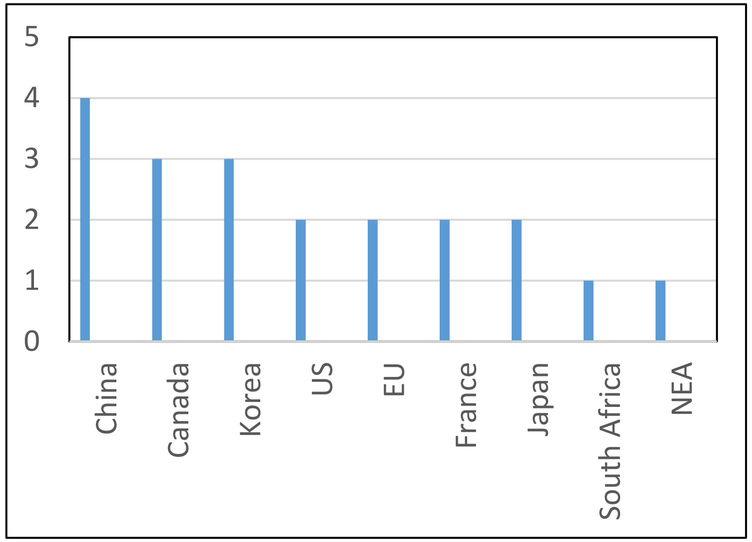
Overview of VHTR HP PMB

Name	First Name	Function	Email
SUPPIAH	Sam	Chair	sam.suppiah@cnl.ca
LEE	Tae Hoon	Co-chair	leeth@kaeri.re.kr
DOMINGUEZ	Maria-Theresa	Member	mdb@empre.es
TAKEGAMI	Hiroaki	Member	takegami.hiroaki@jaea.go.jp
SARRADE	Stephane	Member	stephane.sarrade@cea.fr
O'BRIEN	Jim	Member	james.obrien@inl.gov
LE NAOUR	François	Substitute	francois.le-naour@cea.fr
ROEB	Martin	Substitute	martin.roeb@dlr.de
MYAGMARJAV	Odtsetseg	Substitute	odtsetseg.myagmarjav@jaea.go.jp
ZHANG	Ping	Observer	zhangping77@mail.tsinghua.edu.cn
CHANG	Sunyoung	Technical Secretary	sunyoung.chang@oecd-nea.org

PMB Members (as of March 2020)

PMB Meetings & Chairmanship History

No.	Date	Location	Host
1	26-28 Mar., 2008	San Diego (USA)	INL
2	23-24 Oct., 2008	Madrid (Spain)	JRC
3	16-17 April, 2009	Chicago (USA)	INL
4	7-8 Sep., 2009	NEA (France)	NEA
5	21-22 April 2010	Potchefstroom(RSA)	RSA
6	13-15 Sep., 2010	Daejeon (Korea)	KAERI
7	14-16 June, 2011	Ontario (Canada)	CNL
8	21-23 Sep., 2011	Beijing (China)	INET
9	31 May-1 June, 2012	CNL (Canada)	CNL
10	25-26 Oct., 2012	Oarai (Japan)	JAEA
11	11-12 Apr., 2013	Daejeon (Korea)	KAERI
12	23-24 Sep., 2013	Beijing (China)	INET
13	11-12 Mar., 2014	Grenoble (France)	CEA
14	3-4 Dec., 2014	Beijing (China)	INET
15	3-4 Oct., 2016	CNL (Canada)	CNL
16	17-19 Oct., 2017	Julich (Germany)	JRC
17	18-19 July, 2018	JAEA (Japan)	JAEA
18	7-8 Nov., 2018	Seoul (Korea)	KAERI
19	15-17 May, 2019	Grenoble (France)	CEA
20	20-21 Nov. 2019	Shanghai (China)	INET



Meeting No.	Chair	Co-Chair
1-3	Carl Sink (USA)	Nariaki Sakaba (Japan)
4	Carl Sink (USA)	Pascal Yvon (France)
5-8	Sam Suppiah (Canada)	Young-Joon Shin (Korea)
9-12	Young-Joon Shin (Korea)	Sam Suppiah (Canada)
13-14	Francois Le Naour (France)	Sam Suppiah (Canada)
15-	Sam Suppiah (Canada)	Tae Hoon Lee (Korea)

THE GENERATION IV INTERNATIONAL PROJECT ARRANGEMENT ON HYDROGEN PRODUCTION

GEN IV International Forum℠

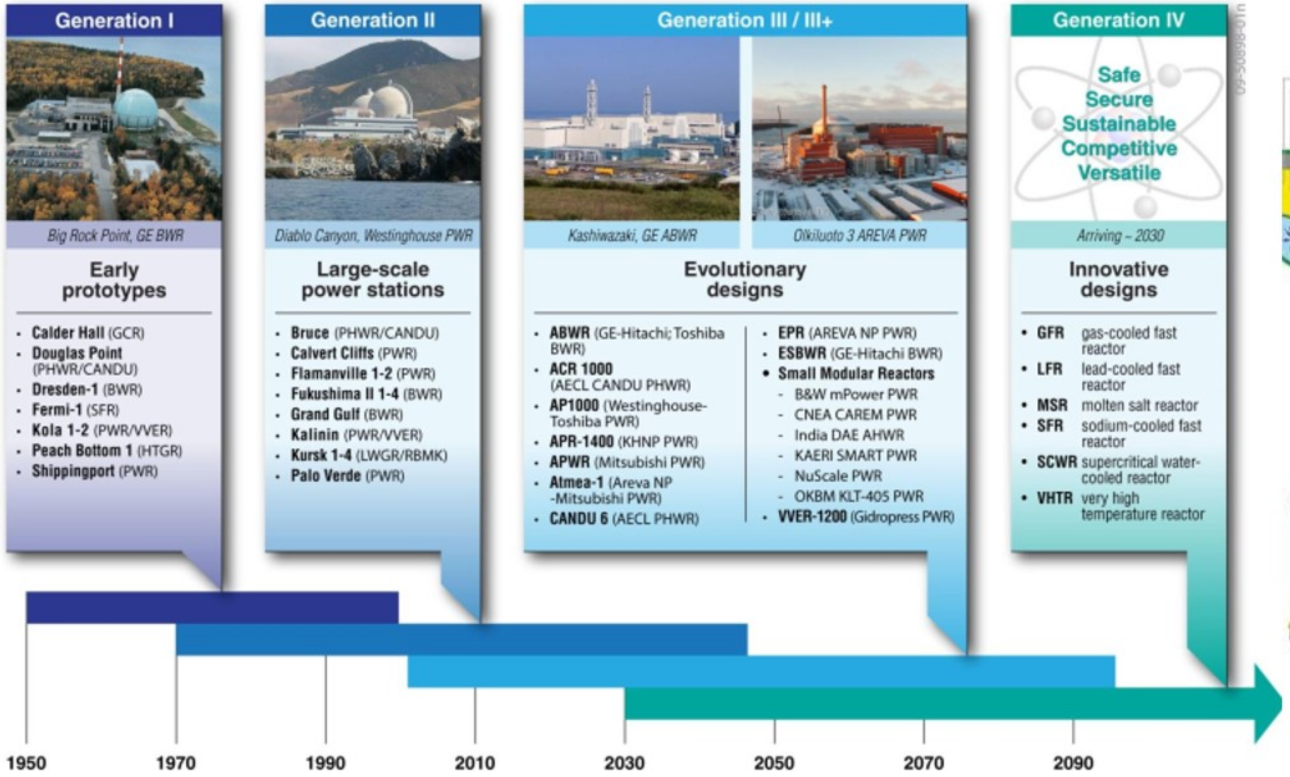
HP PA	Effective Since 19-Mar-18	CA	EU	FR	JP	CN	KR	US
		X	X	X	X	O	X	X

Date	Event
19 March 2008	• All of the VHTR HP PA signatories signed the VHTR HP PA for a period of ten (10 years).
5-6 November 2012	• The SSC approved the accession to the PA of INET.
19 March 2018	• 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.
Being processed	• The PMB finalized the updated project plan adding INET's contribution.
To be processed	• The SSC approved the updated project plan adding INET's contribution.
To be processed	• The PA amended by adding INET as a new Signatory.

VHTR R&D Project
Hydrogen Production Project Plan

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.

Generation IV Nuclear Reactor Systems



Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

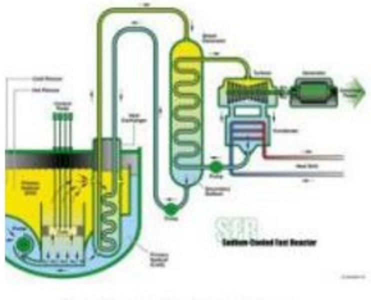
Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

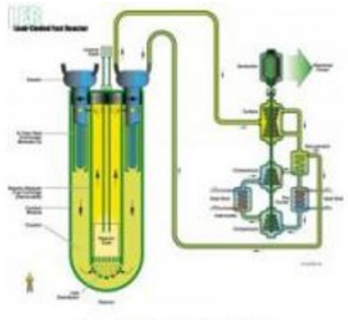
Arriving – 2030

Innovative designs

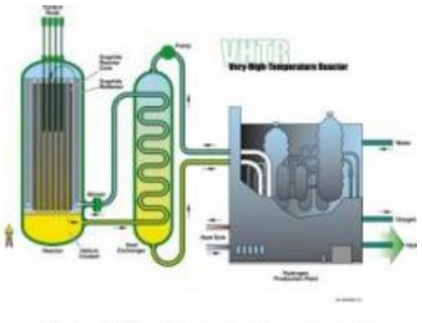
GFR	gas-cooled fast reactor
LFR	lead-cooled fast reactor
MSR	molten salt reactor
SFR	sodium-cooled fast reactor
SCWR	supercritical water-cooled reactor
VHTR	very high temperature reactor



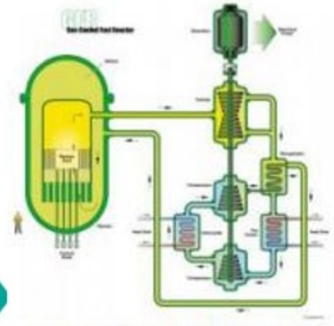
Sodium Fast Reactor



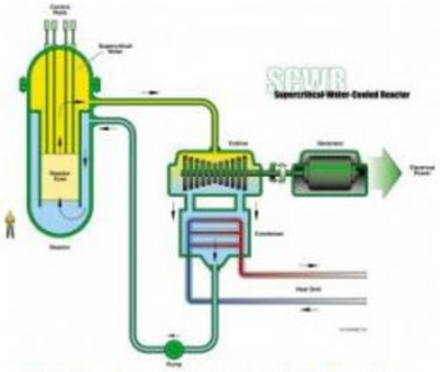
Lead Fast Reactor



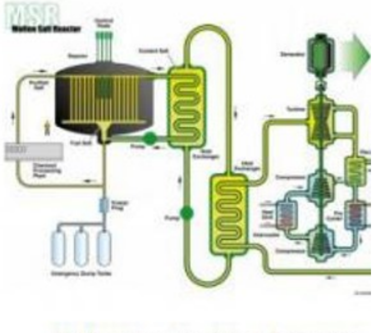
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

Hydrogen – A Critical Energy Carrier For Future

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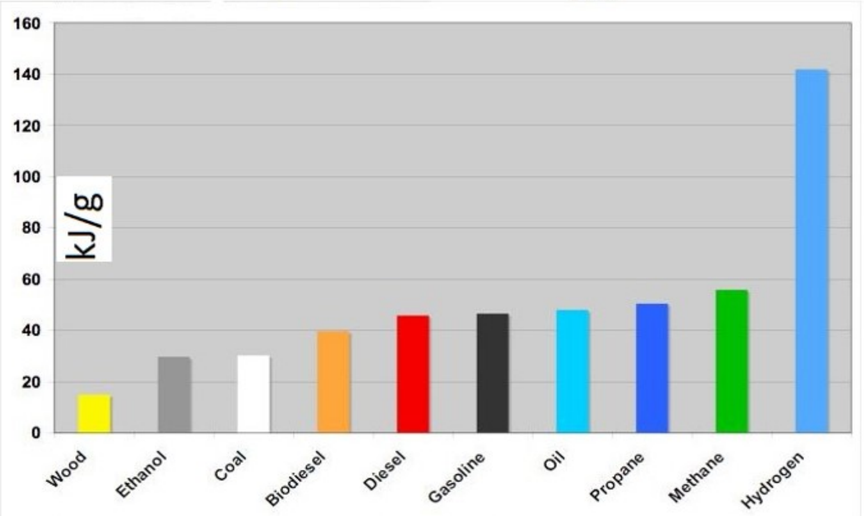
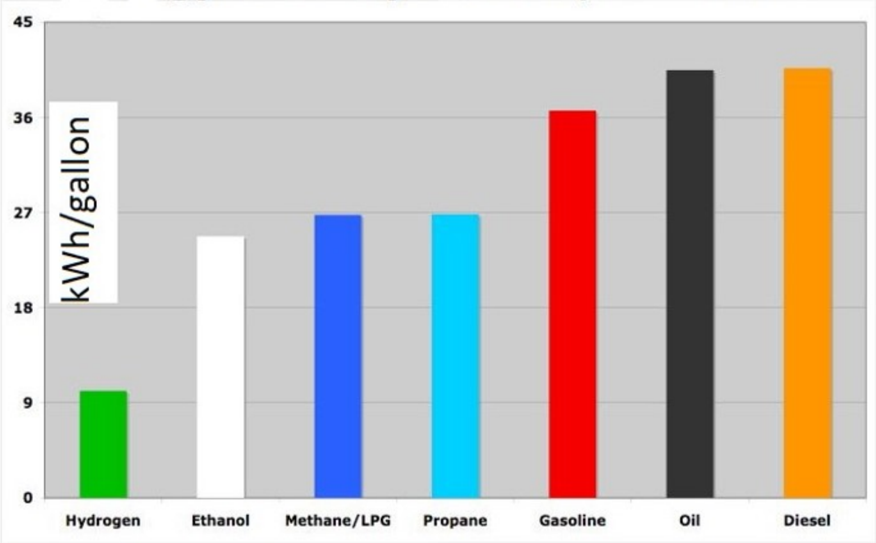
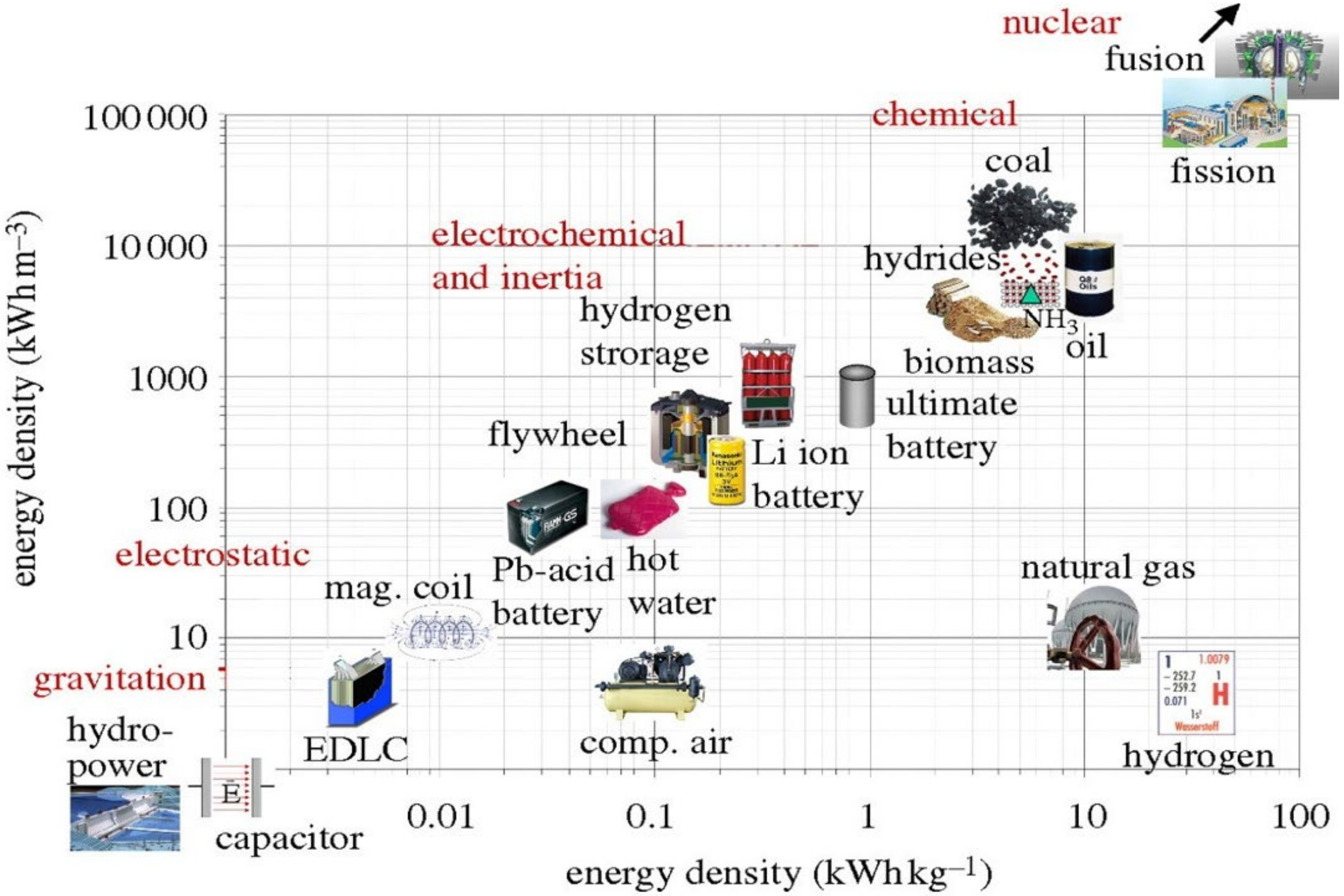
Specific Energy



Energy Density: KWH per Gallon

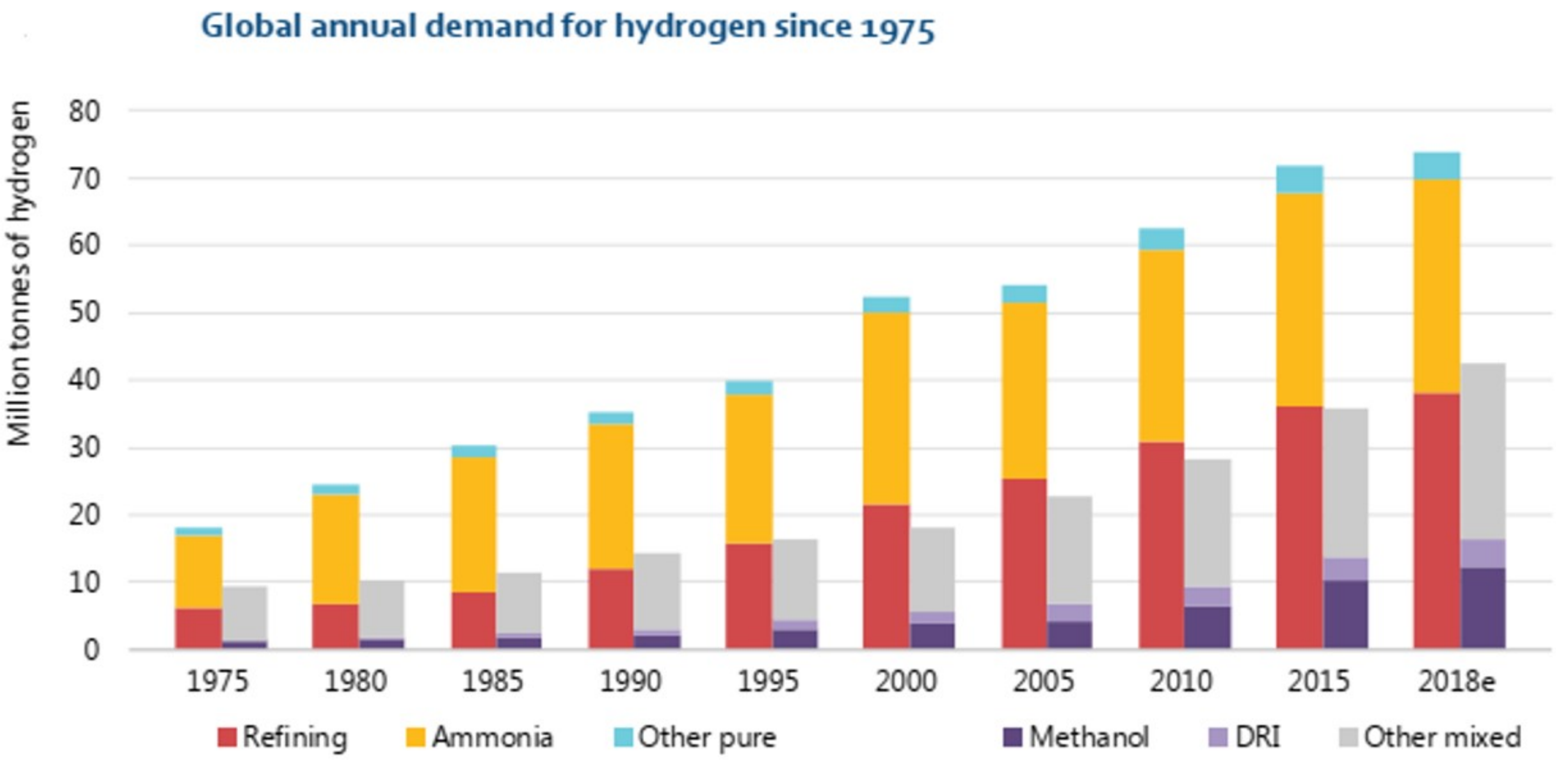


Source: DOE, Green Econometrics research



A. Zuttel et.al., Phil. Trans. R. Soc. A(2010), 368, 3329-3342

Current & Future Demand & Use of Hydrogen

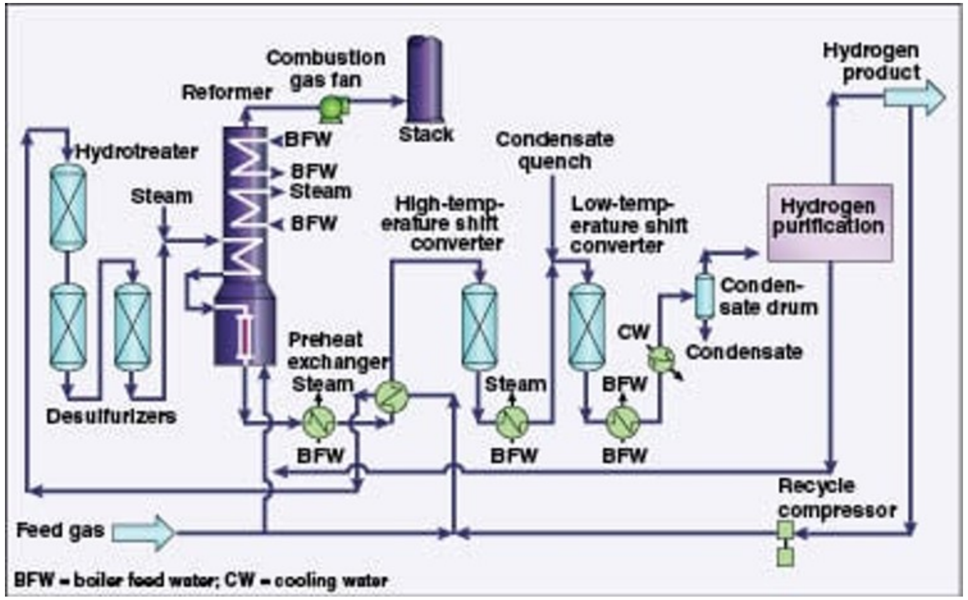


Transportation:
- Heavy vehicles
- Trains
- Ships
- Aviation

IEA (2019), "The Future of Hydrogen", IEA, Paris https://www.iea.org/reports/the-future-of-hydrogen

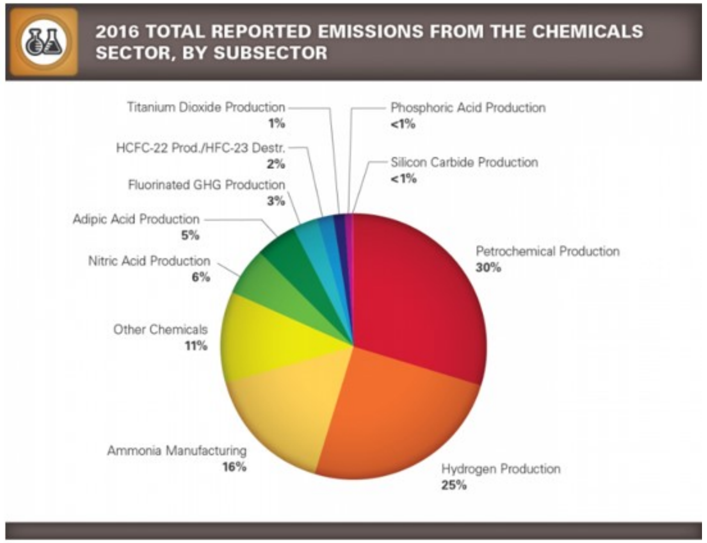
Current Hydrogen Production

- Fossil source
  - –Steam Methane Reforming
  - –Partial oxidation
  - –Biomass
  - –Others
- Non-fossil energy source
  - –Advanced Alkaline Electrolysis
  - –PEM Electrolysis

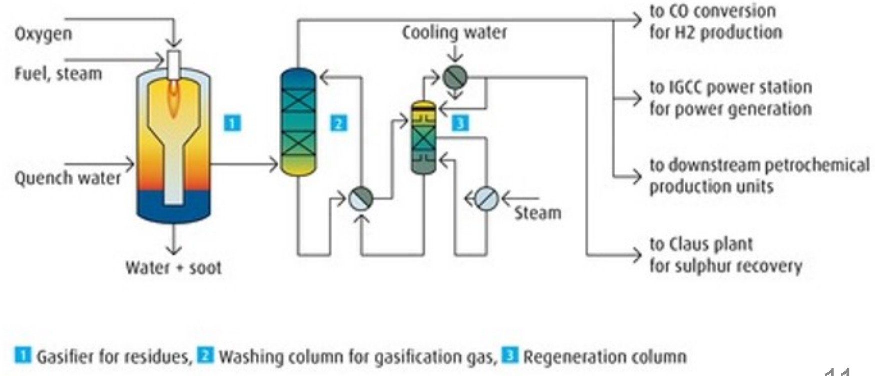


BFW = boiler feed water; CW = cooling water

ETIP Wind – Wind2H$_2$| Brussels (BE) | 21.02.2019

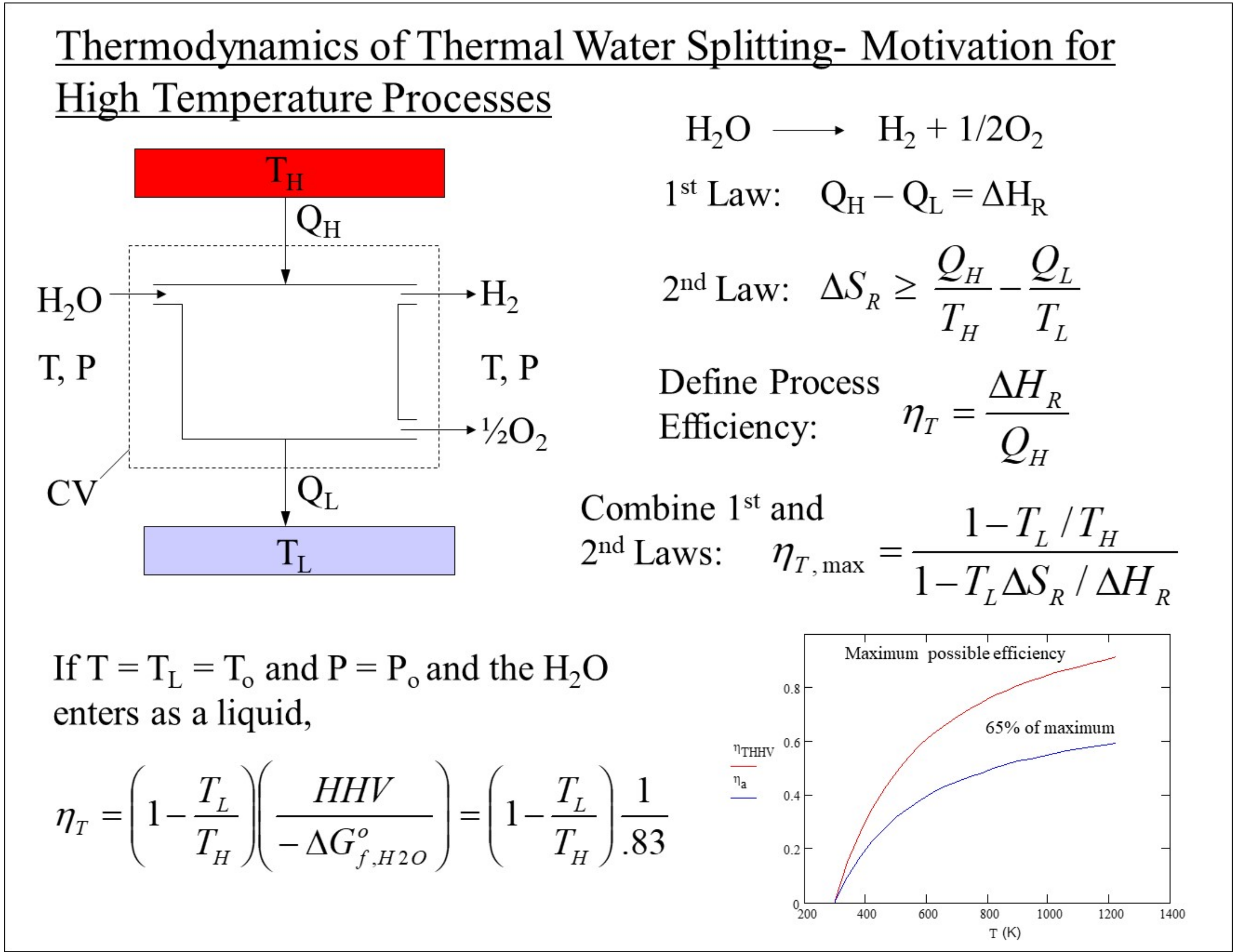


2016 TOTAL REPORTED EMISSIONS FROM THE CHEMICALS SECTOR, BY SUBSECTOR



1 Gasifier for residues, 2 Washing column for gasification gas, 3 Regeneration column

Why High Temperature Processes?



Thermodynamics of Thermal Water Splitting- Motivation for High Temperature Processes

$$H_2O \longrightarrow H_2 + 1/2O_2$$

1st Law: $Q_H - Q_L = \Delta H_R$

2nd Law: $\Delta S_R \geq \frac{Q_H}{T_H} - \frac{Q_L}{T_L}$

Define Process Efficiency: $\eta_T = \frac{\Delta H_R}{Q_H}$

Combine 1st and 2nd Laws: $\eta_{T,\max} = \frac{1 - T_L / T_H}{1 - T_L \Delta S_R / \Delta H_R}$

If $T = T_L = T_o$ and $P = P_o$ and the H_2O enters as a liquid,

$$\eta_T = \left(1 - \frac{T_L}{T_H}\right)\left(\frac{HHV}{-\Delta G^o_{f,H2O}}\right) = \left(1 - \frac{T_L}{T_H}\right)\frac{1}{.83}$$

Hydrogen from GEN IV Nuclear Technologies

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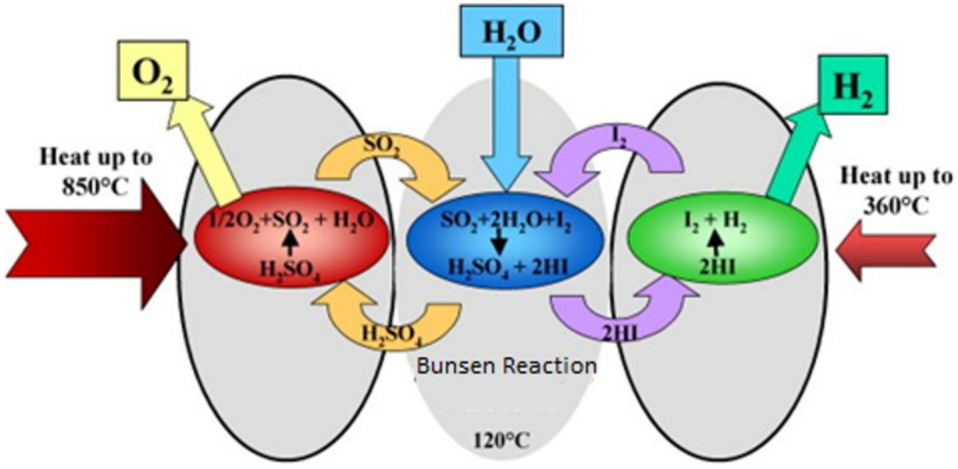
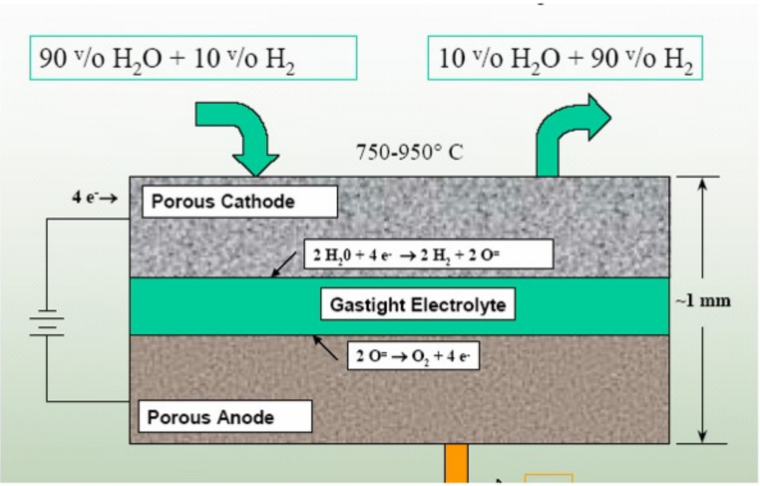
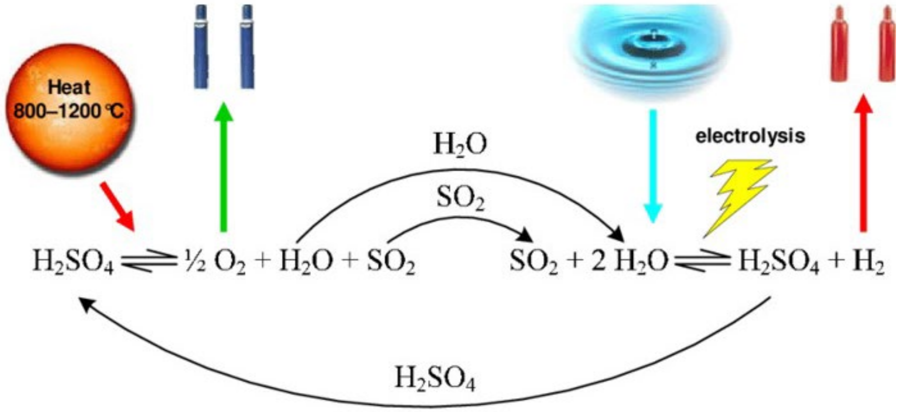


Sulphur-Iodine Process

Copper-Chlorine Process



High Temperature Steam Electrolysis



Hybrid-Sulfur Process

H_2 Production PMB Goals and Objectives

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.

H_2 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 CO_2 while integrating different primary energy sources

H_2 Production PMB Goals and Objectives (cont.)

Development of Copper-Chlorine (Cu-Cl) Cycle and Assessment of other alternative cycles and economic evaluation

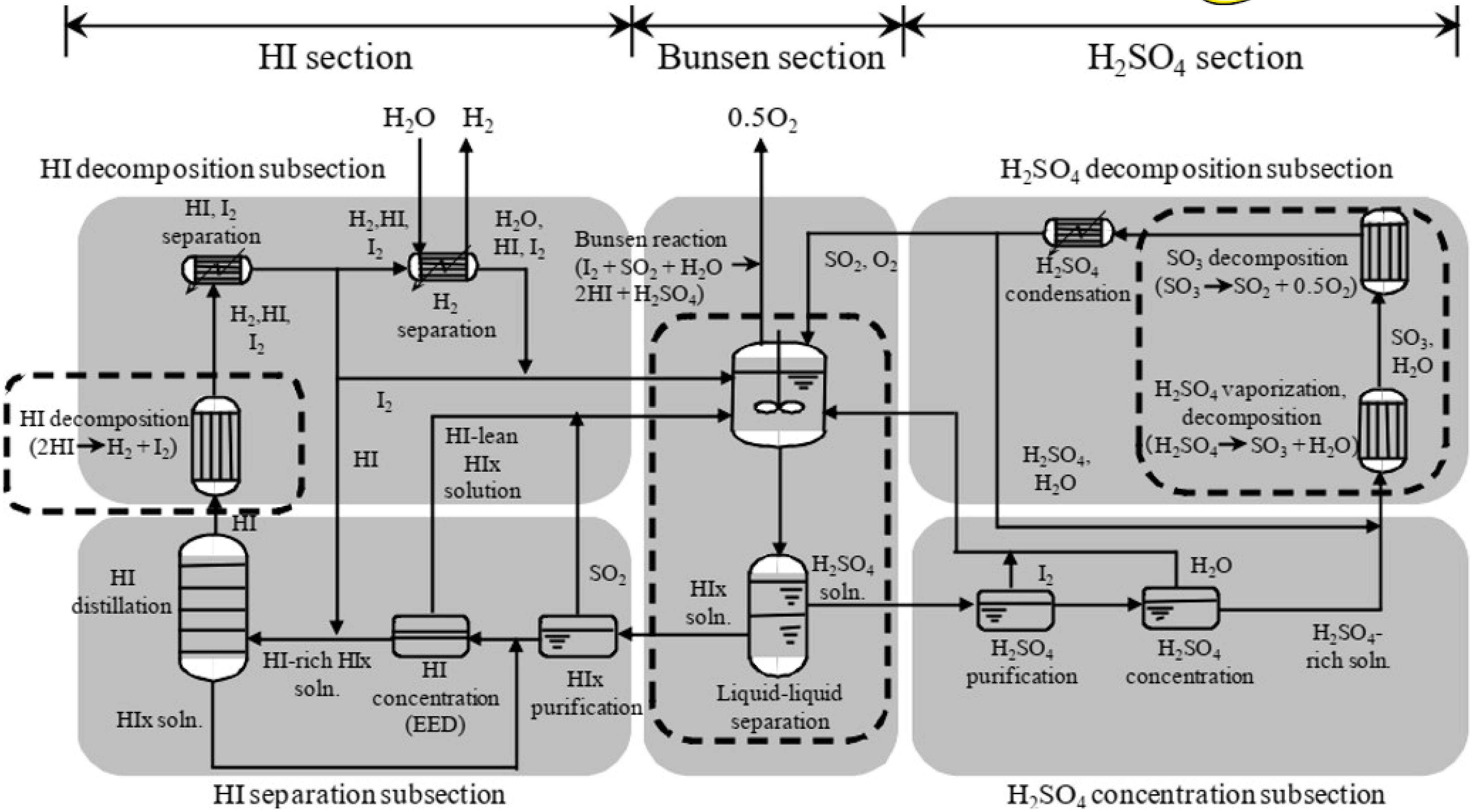
- Cu-Cl Cycle evaluation including determination of process options, flow-sheet optimization and selection of materials.
- Cu-Cl Cycle component and bench-scale experiments to define and evaluate key parameters such as thermodynamic properties, rate constants, and equipment selection.
- Integrated testing of lab-scale system for 100 L/h hydrogen production.
- Development of HyS process: SO_2 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.*

H_2 Production PMB Goals and Objectives (cont.)

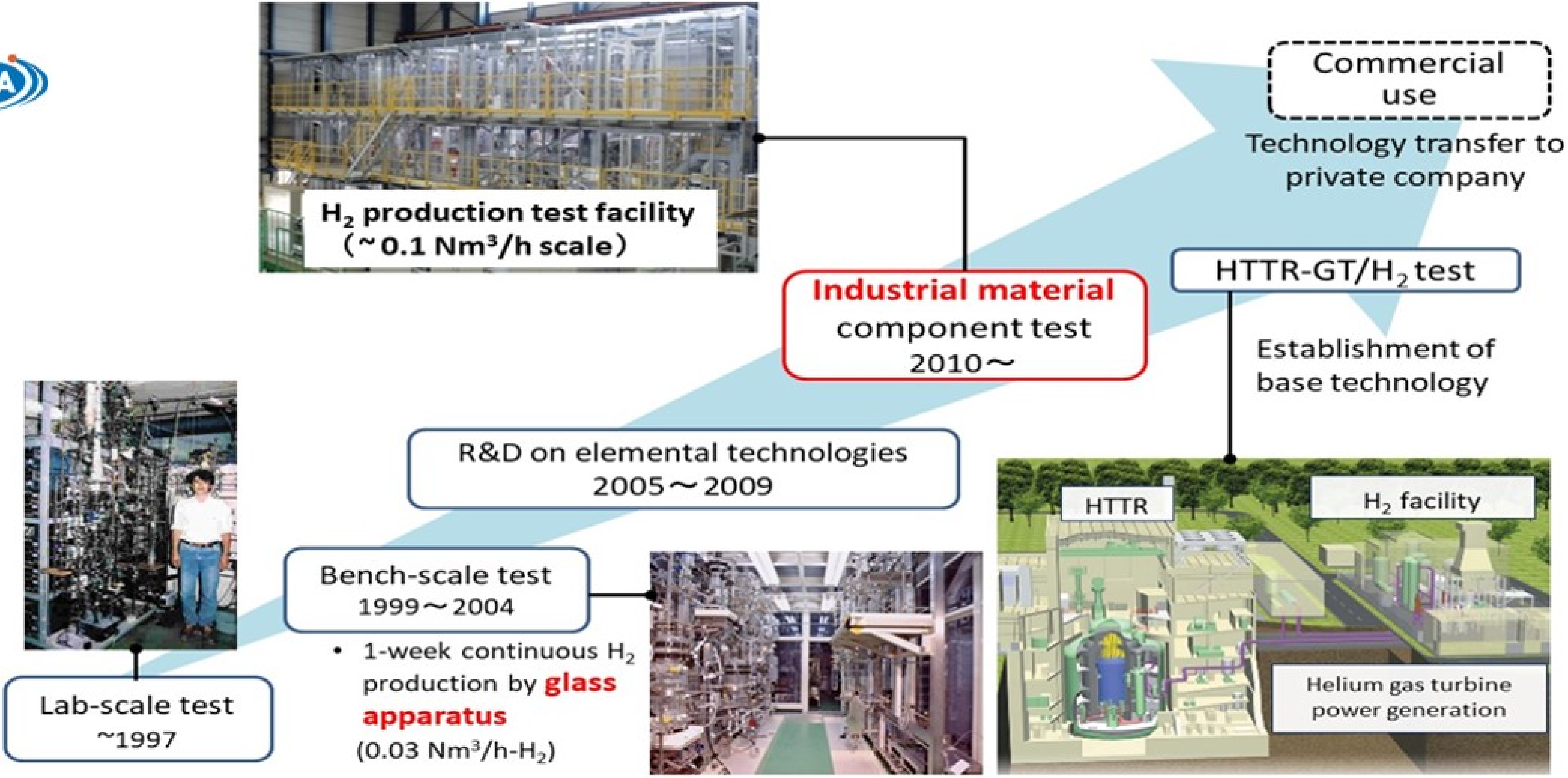
Hydrogen Production and Nuclear Reactor Coupling

- 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



Lab-scale test
~1997

Bench-scale test
1999～2004

- 1-week continuous H_2 production by **glass apparatus** ($0.03\ Nm^3/h\text{-}H_2$)

R&D on elemental technologies
2005～2009

Industrial material
component test
2010～

H_2 production test facility
(~$0.1\ Nm^3/h$ scale)

HTTR-GT/H_2 test

Establishment of base technology

Commercial use

Technology transfer to private company

JAEA Time-line on H_2 Production Developments Using Sulfur-Iodine Process

- **Continuous H_2 production integrated 3 sections**

  Date: October 2016

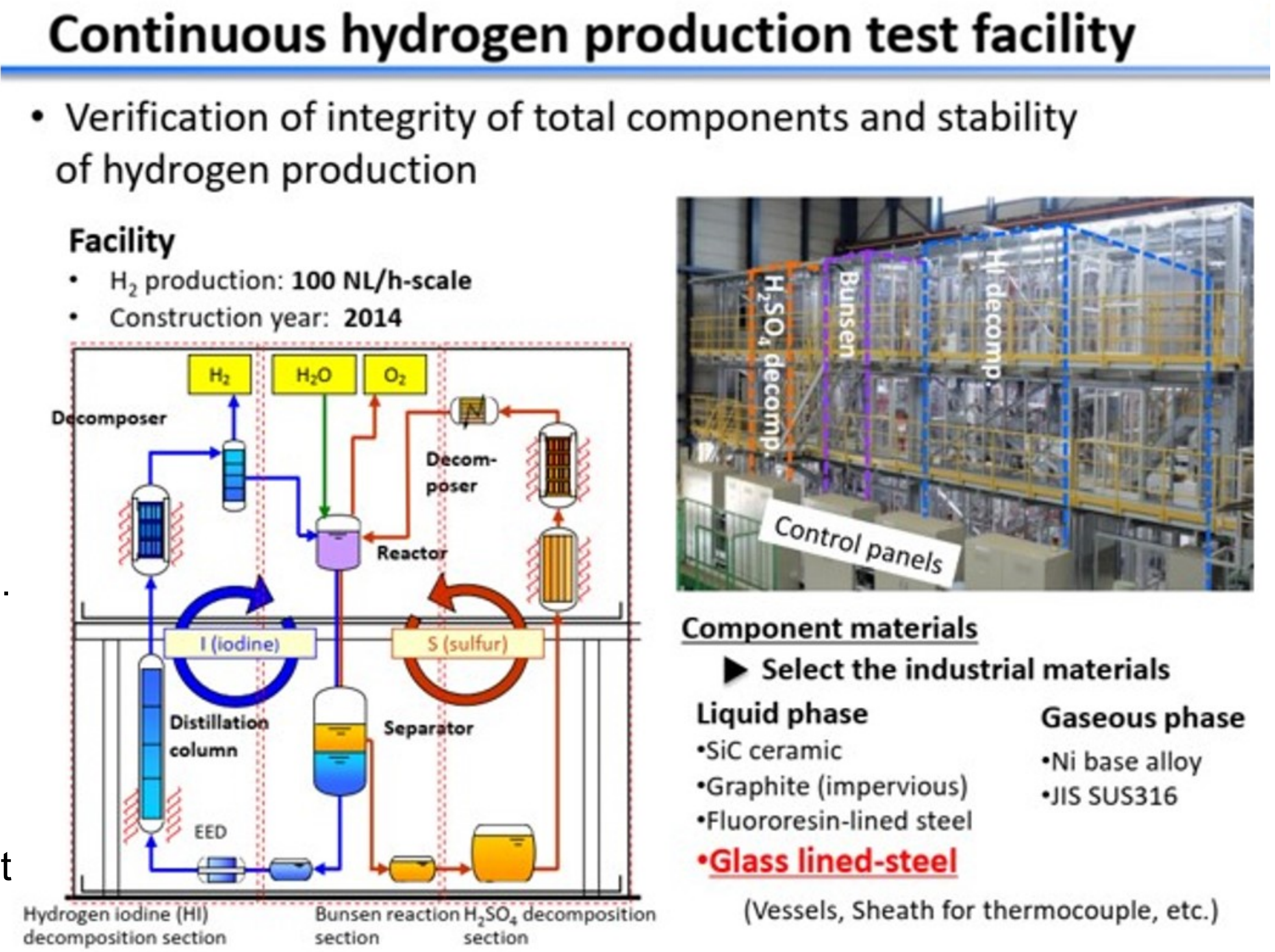
  Rate: 20 L/h

  Operation time: 31 hours
  - The developed HIx solution transport technology was confirmed.
  - The technology to prevent I_2 precipitation in HI decomposition section was confirmed.
- **Long-term continuous H_2 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 H_2 production test**.
  - Higher H_2 production tests are planned to acquire a set of data with a range varying composition, and development of an automatic control system.



Continuous hydrogen production test facility

- Verification of integrity of total components and stability of hydrogen production

Facility

- H_2 production: **100 NL/h-scale**
- Construction year: **2014**

Component materials

▶ Select the industrial materials

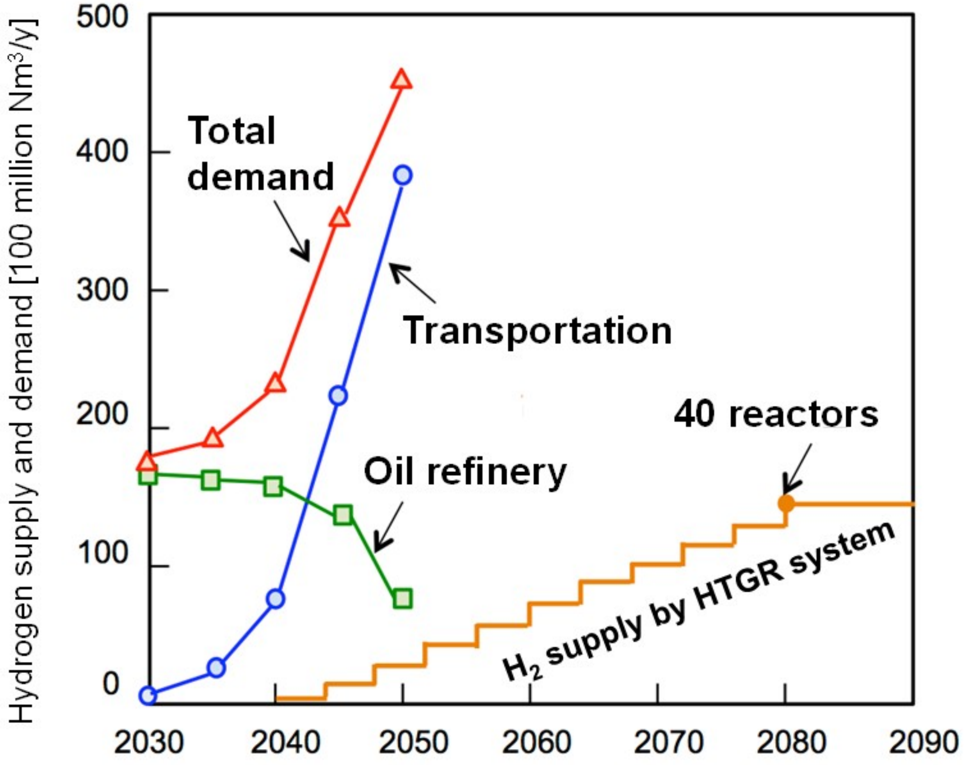
Liquid phase	Gaseous phase
•SiC ceramic	•Ni base alloy
•Graphite (impervious)	•JIS SUS316
•Fluororesin-lined steel	
•Glass lined-steel	

(Vessels, Sheath for thermocouple, etc.)

*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.



Estimation of hydrogen demand[1] and HTGR hydrogen supply

Site location

Domestic

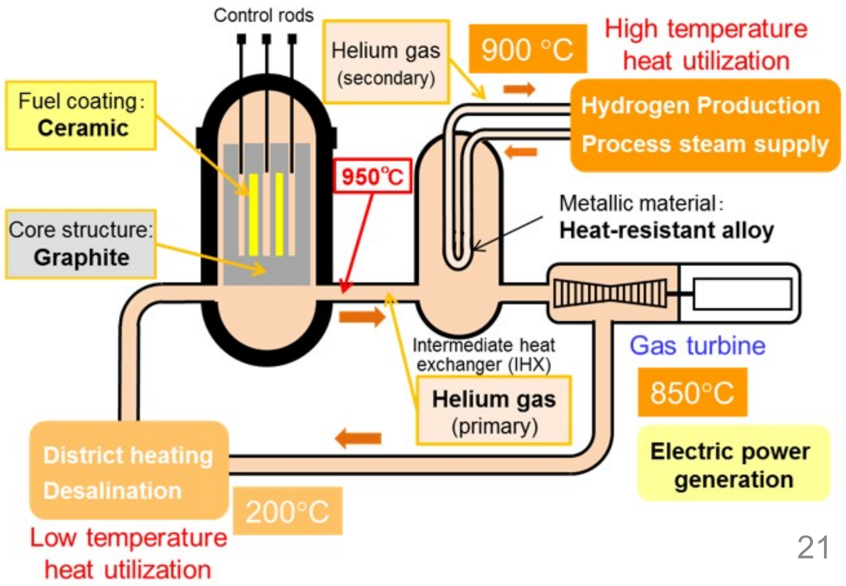
Installation in sites of existing nuclear power plant

Overseas

Installation in developing nations as hydrogen supplier

HTGR cogeneration system for hydrogen and electricity

Reactor thermal power	600 MWt
Power generation	87 MWe
Hydrogen production rate	70,000 Nm^3/h (6.2 ton/h)



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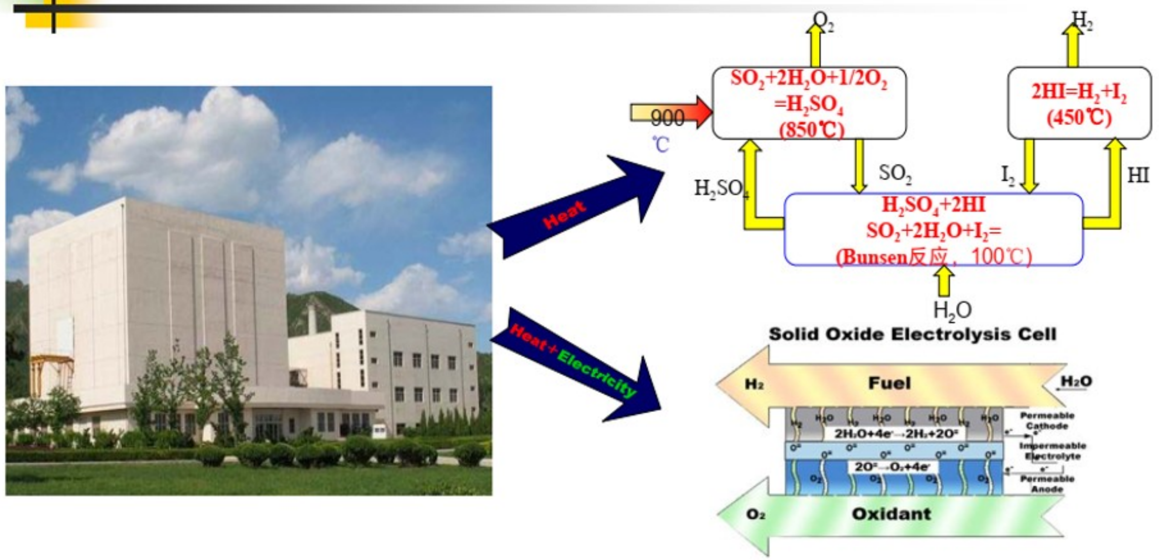
[1] http://www.iae.or.jp/wp/wp-content/uploads/2014/09/ap_fy2014_r2.pdf

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.

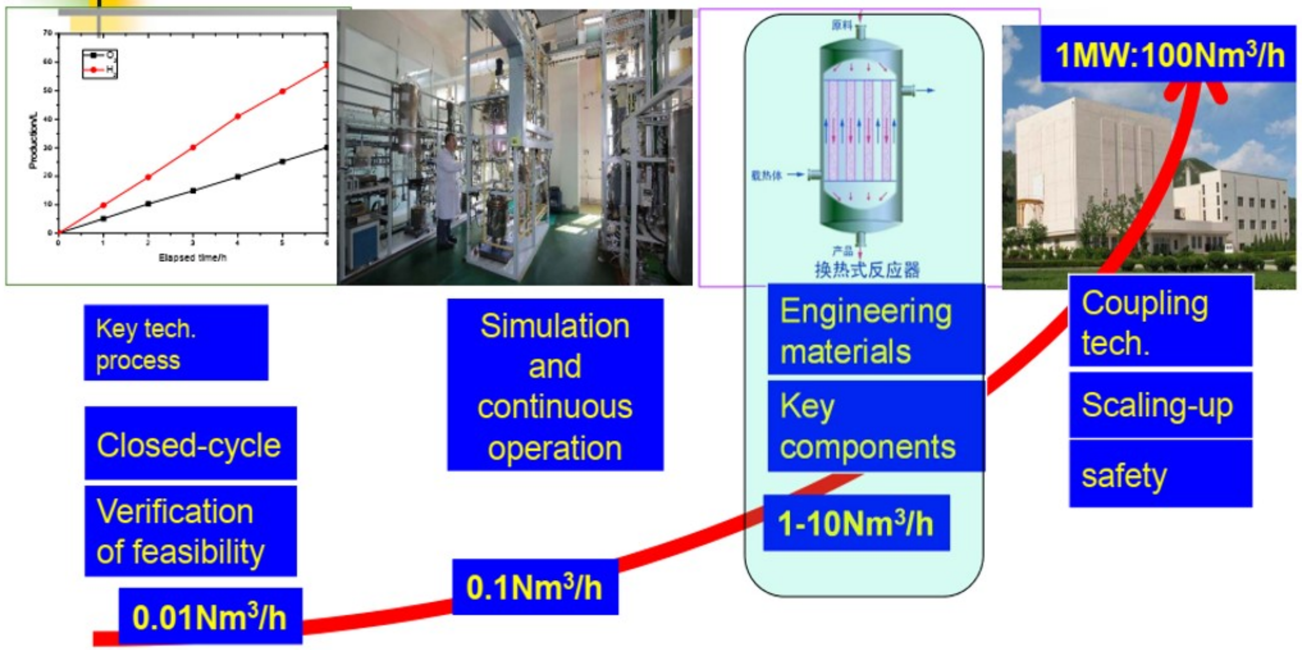
INET’s Efforts for a Low-Carbon Economy (China)

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

Closed-cycle

Verification of feasibility

0.01Nm^3/h

Simulation and continuous operation

0.1Nm^3/h

Engineering materials

Key components

1-10Nm^3/h

1MW:100Nm^3/h

Coupling tech.

Scaling-up

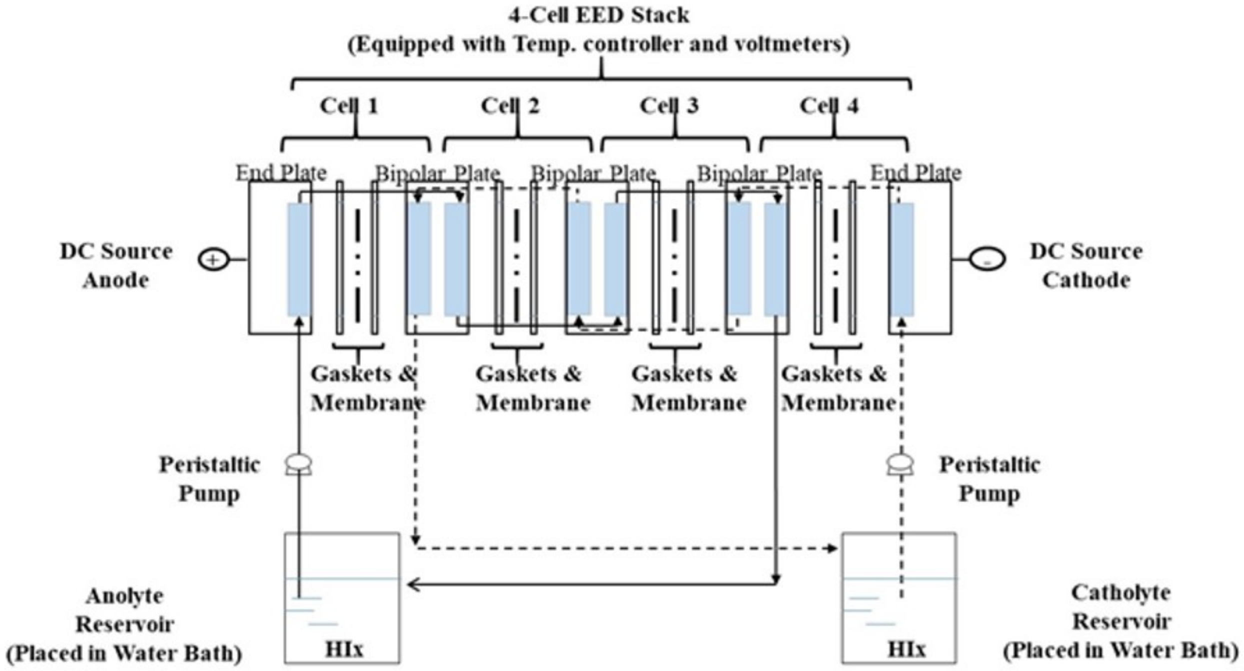
safety

Fundamental study	System integration	Key components	Pilot demo
2005-2010	2010-2015	2016-2020	2021-2025

P Zhang, et al. ***Renewable & Sustainable Energy Reviews***,. https://doi.org/10.1016/j.rser.2017.05.275

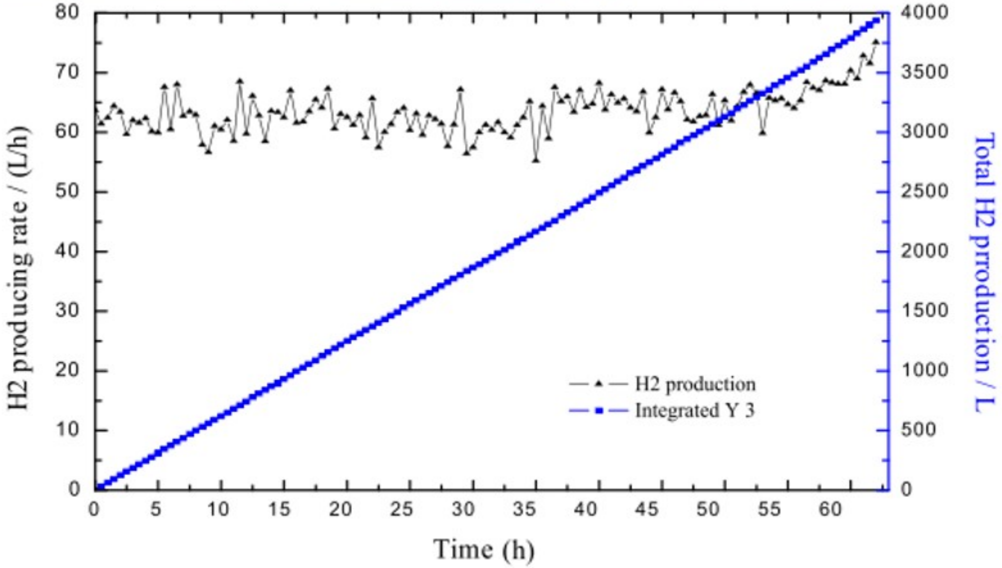
Current & Future R&D Activities in China

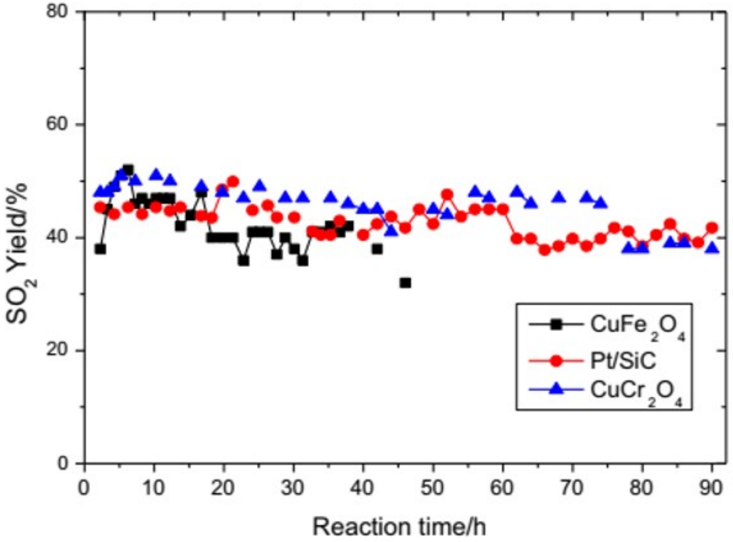
- Development of the key reactor components
  - Sulfuric acid decomposer
  - HI decomposer
  - Bunsen reactor
  - EED
- Dynamic simulation
- Pilot scale IS development (two phases, ~ 10years)
  - Safety issues on nuclear hydrogen
  - Key technologies of pilot scale
    - Engineering materials
    - Reactors, 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℃)
  - IHX



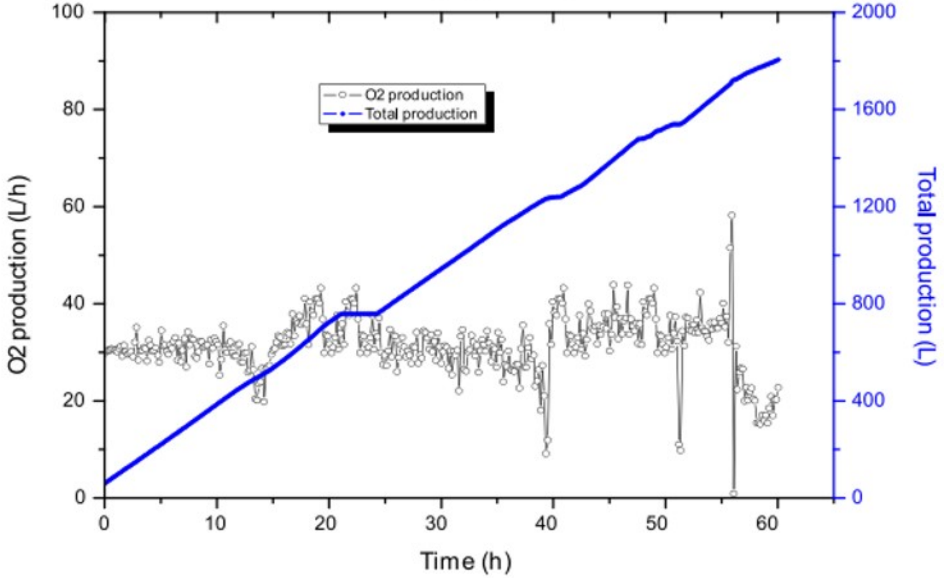
Current density : 200mA/cm^2

Some Operational Results from Longest Test Conducted at INET



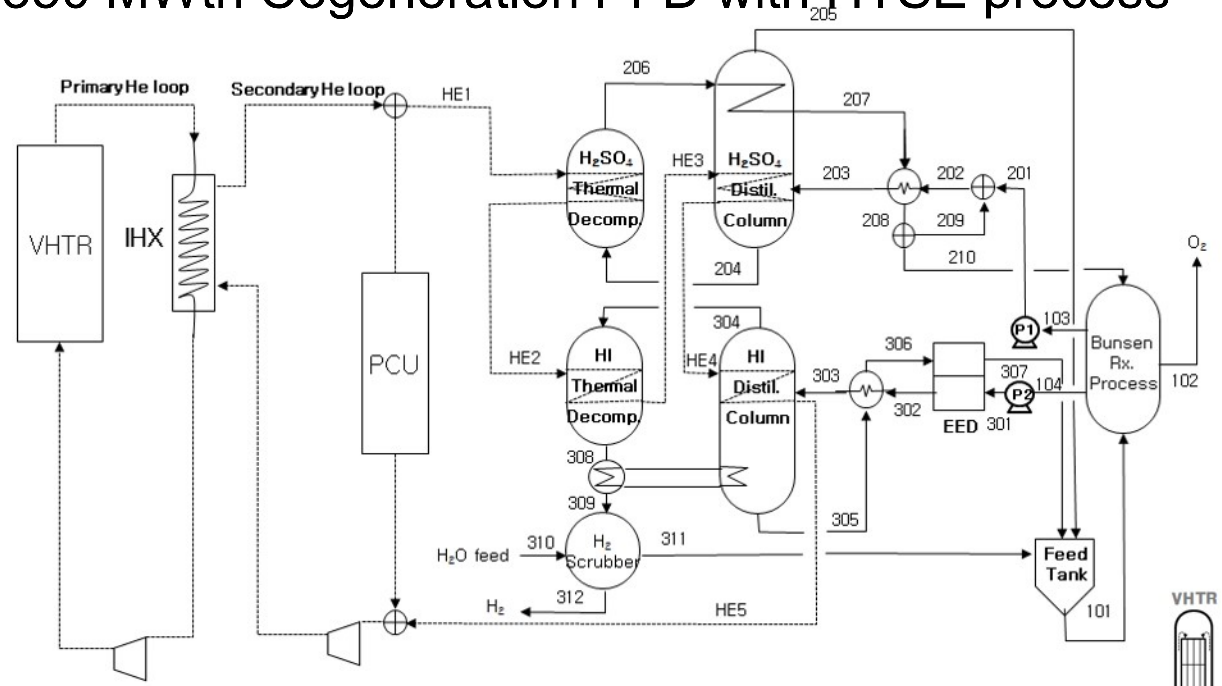


H_2SO_4 Decomposer Catalyst tests

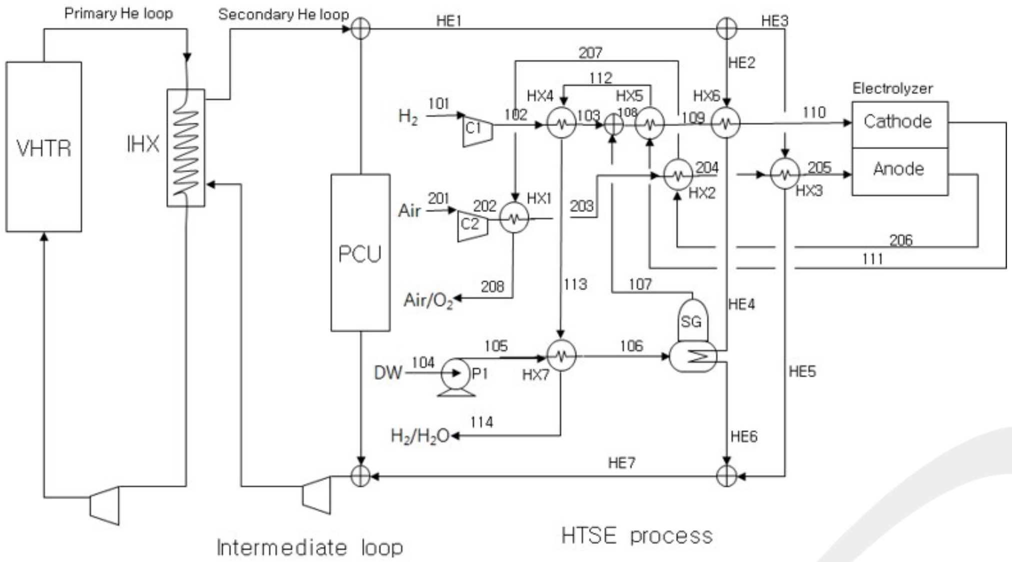


Update of Korean H_2 Related R&D Status

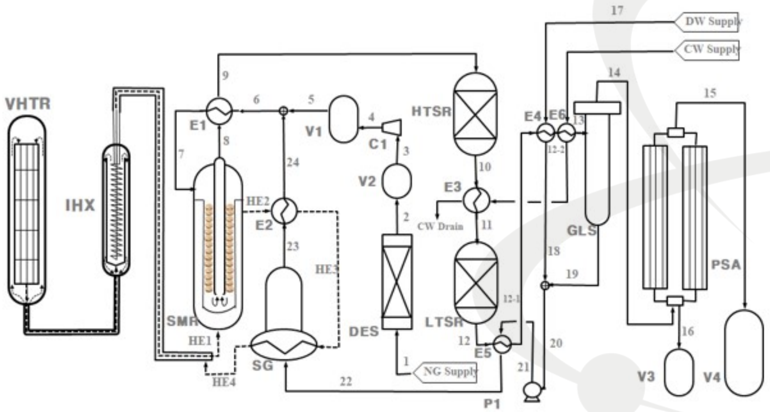
- Earlier focus on Sulphur-Iodine process developments
- Hydrogen Production Process coupled to the HTGR
- 350 MWth Cogeneration PFD with HTSE process



<SI process PFD>



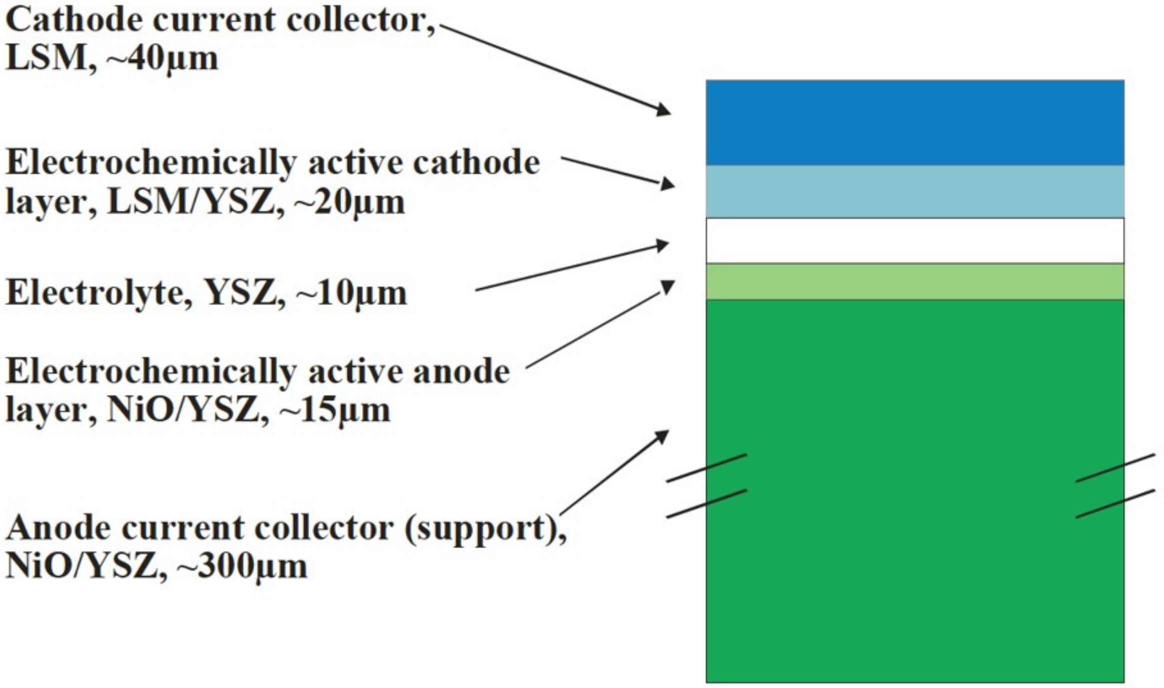
<HTSE process PFD>



<SMR process PFD>

HTSE Leverages Fuel Cell Technology

Layers in a typical electrode-supported cell



Cathode current collector, LSM, ~40µm

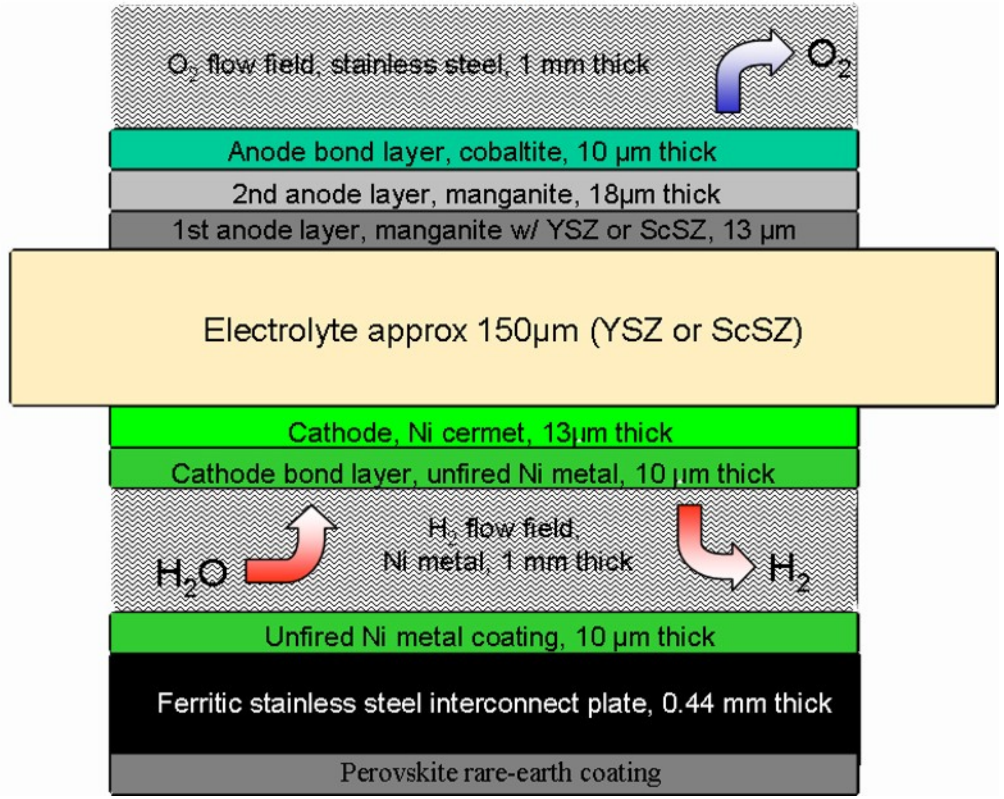
Electrochemically active cathode layer, LSM/YSZ, ~20µm

Electrolyte, YSZ, ~10µm

Electrochemically active anode layer, NiO/YSZ, ~15µm

Anode current collector (support), NiO/YSZ, ~300µm

SOEC stack repeat unit



O_2 flow field, stainless steel, 1 mm thick

O_2

Anode bond layer, cobaltite, 10 µm thick

2nd anode layer, manganite, 18µm thick

1st anode layer, manganite w/ YSZ or ScSZ, 13 µm

Electrolyte approx 150µm (YSZ or ScSZ)

Cathode, Ni cermet, 13µm thick

Cathode bond layer, unfired Ni metal, 10 µm thick

H_2O

H_2 flow field, Ni metal, 1 mm thick

H_2

Unfired Ni metal coating, 10 µm thick

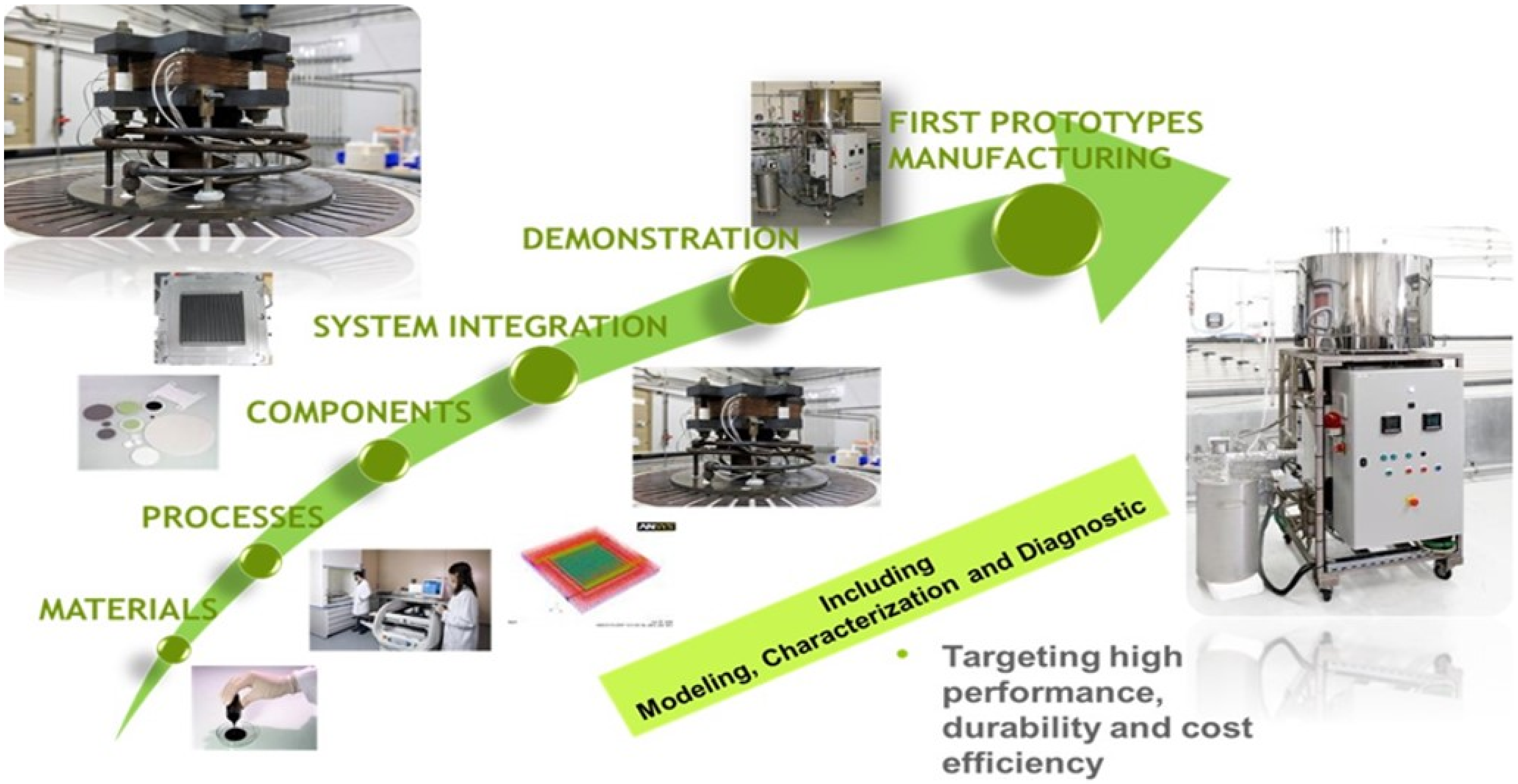
Ferritic stainless steel interconnect plate, 0.44 mm thick

Perovskite rare-earth coating

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

CEA Focus on HTSE



FIRST PROTOTYPES MANUFACTURING

DEMONSTRATION

SYSTEM INTEGRATION

COMPONENTS

PROCESSES

MATERIALS

Including Modeling, Characterization and Diagnostic

- Targeting high performance, durability and cost efficiency

Carbon Free HYDROGEN Production

SOEC : High Temperature Electrolyser, the competitive solution

SYSTEM DEVELOPMENT

In 10 years of R&D :

Performance improvement : **X8**

Lifetime: **> 2500 hours**

SYDNEY
1st integrated system

PISTEUR
In demonstration at a partner site

STACK DEVELOPMENT

Number of cells/stack : **x 25**

1st prototype of integrated system

Demonstrated yield at system level: **87% PCI**

Electrolyzer core
25 cells
Power 3kW

BASIC CONCEPTS DEVELOPMENT

Cost reduction of stack : **-80%**

Background patent portfolio:
40 patent family on stack

Bonus : Reversible Technology

CEA Cell at the state of the art
Characteristics
Working point $1A/cm^2$
Degradation 2-3% 1000h
Active Surface $100cm^2$

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

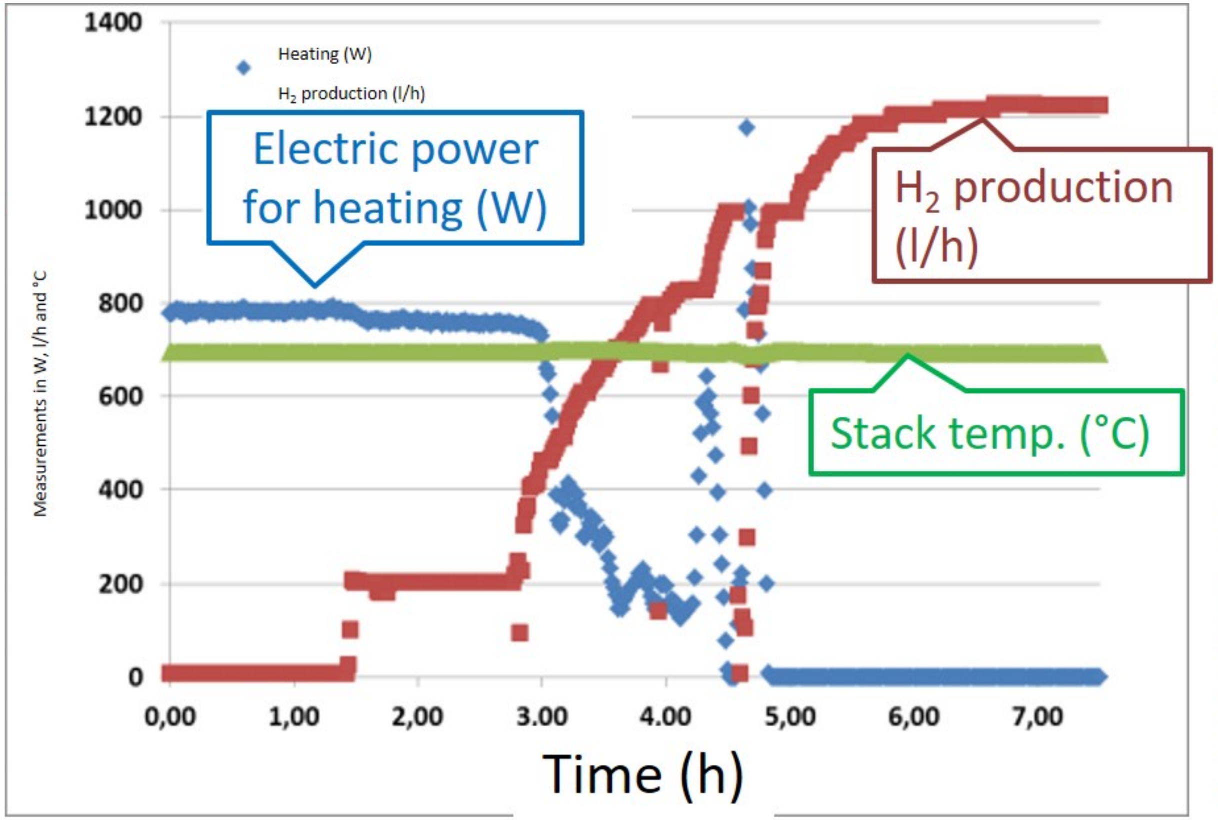
- **2018: 1st reversible system delivered to an industrial (ENGIE)**
  - 1 stack – 1NM3/h of H_2 production, 1 kWe in fuel cell mode
  - Electrical efficiency – 84% in electrolyze mode, 55% in fuel cell mode
  - Time to switch : 15 minutes

- **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

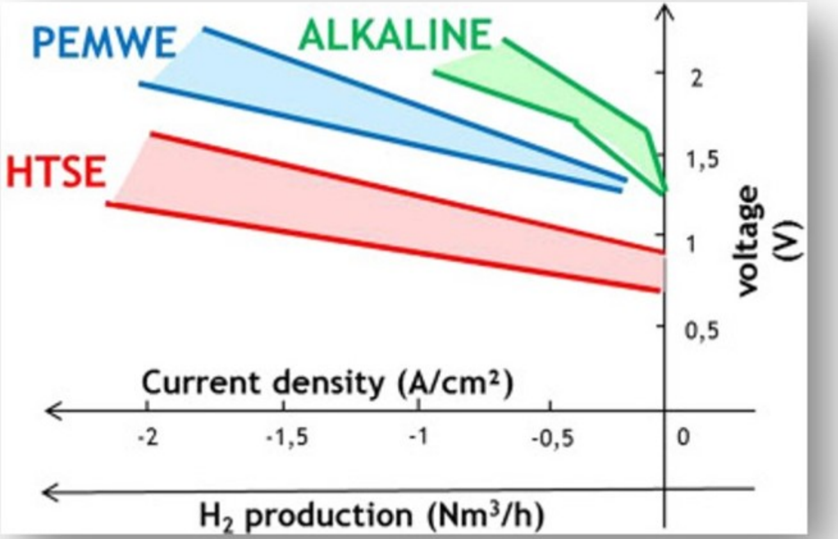
Carbon Free H_2 Production

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



CEA Solid Oxide Electrolyser

HTSE

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

Duration of operation by year

Electricity price (€/Mwh_{el})

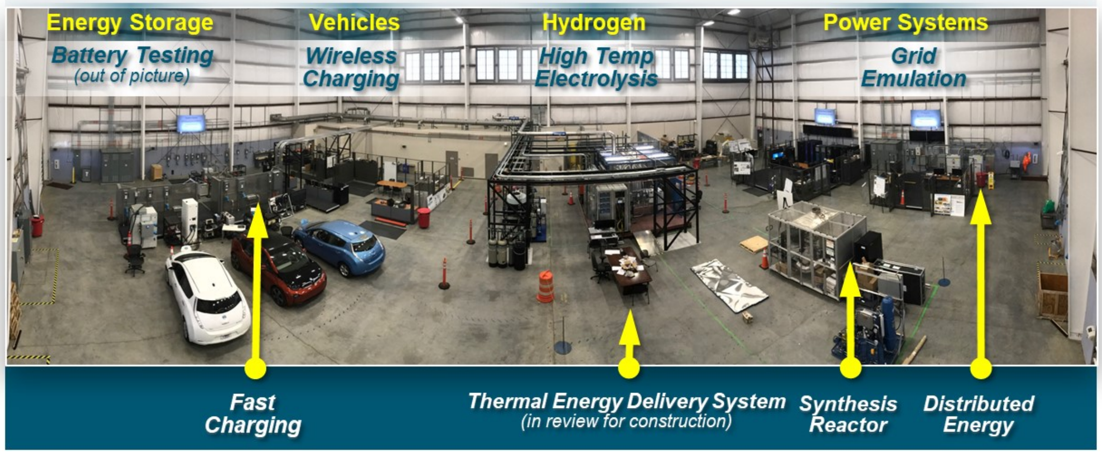
Massification of electrolyzers production (MW/year/plant)	CAPEX of elecytrolyzer system (€/kW)	8200 h	5000h		3000h	
		80	60	40	40	30
1	4000	10,03	12,87	12,48	15,47	15,08
20	1500	4,59	4,15	3,78	4,82	4,45
200	1000	3,91	3,02	2,66	3,23	2,87
1000	400	3,06	1,49	1,14	1,32	0,97

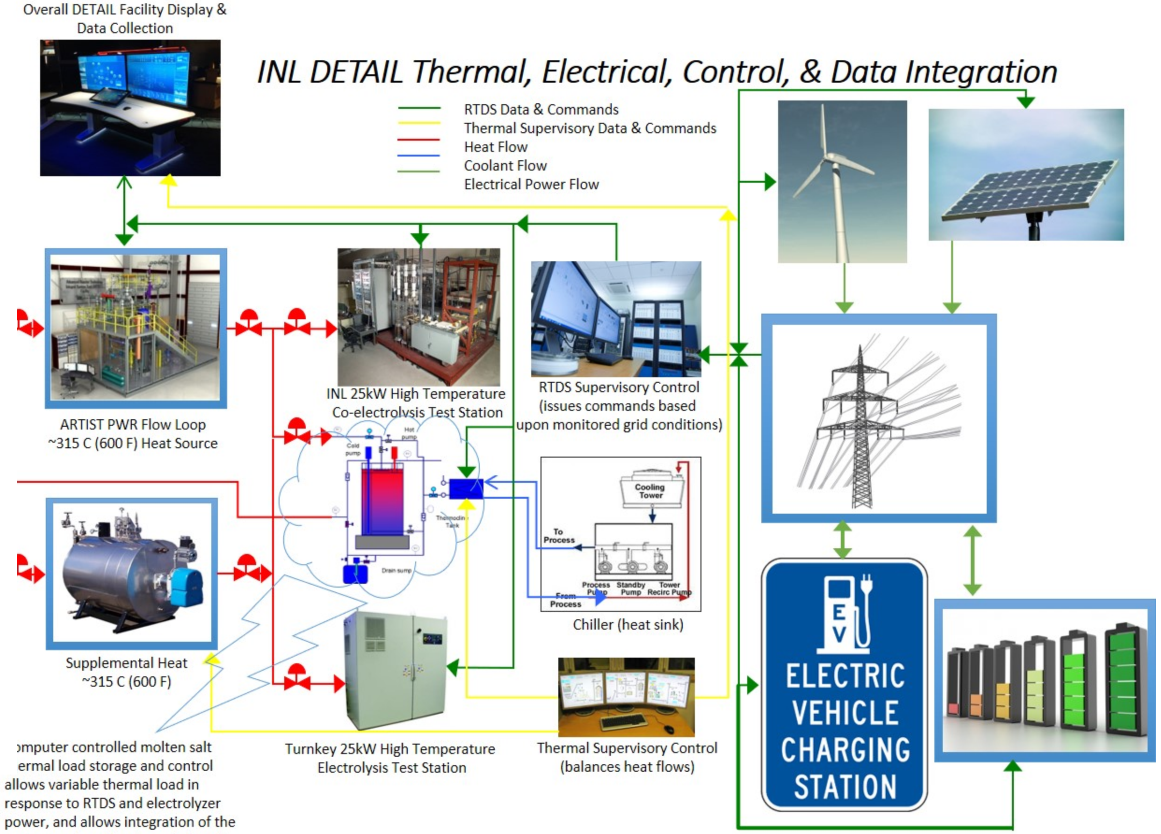
H2 green Production

US Advanced Hydrogen Production Research & Current Efforts for a Low-Carbon Economy

Energy Systems Laboratory

Systems Integration Lab





omputer controlled molten salt ermal load storage and control allows variable thermal load in response to RTDS data and electrolyzer power, and allows integration of the various scales of heat production / consumption. Can be phase change salts.

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

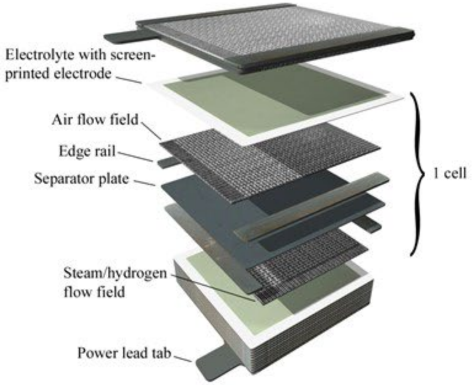
Accomplishments and Progress

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

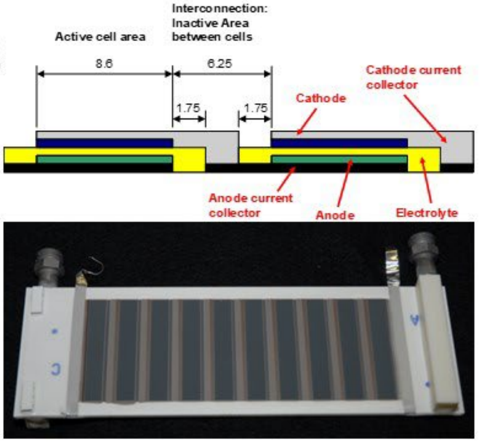
- **Completed Design and Installation of Facility Support Infrastructure**
  - Power, DI water system, drain lift station, enclosure, ventilation system, H2 vent, gas monitoring, safety interlocks, fire protection, structural support systems
- **Completed Design and Installation of 25 KW HTE Test Facility**
  - 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

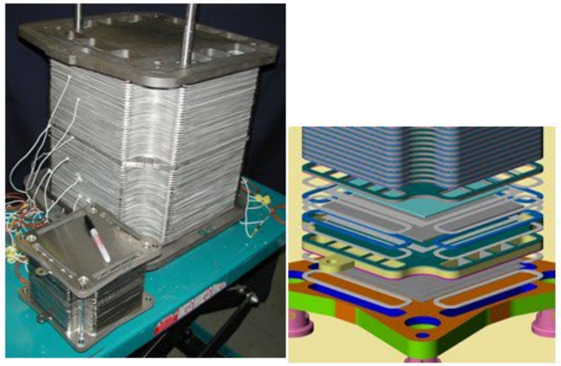
Cell and Stack Designs Studied By INL



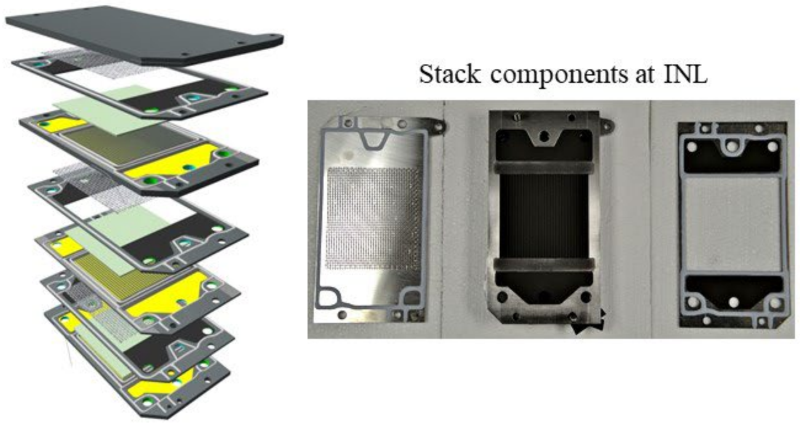
Externally manifolded planar stack, electrolyte-supported cells (Ceramatec)



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



Internally manifolded cross-flow planar stack with anode-supported cells (MSRI, Versa Power)



Stack components at INL

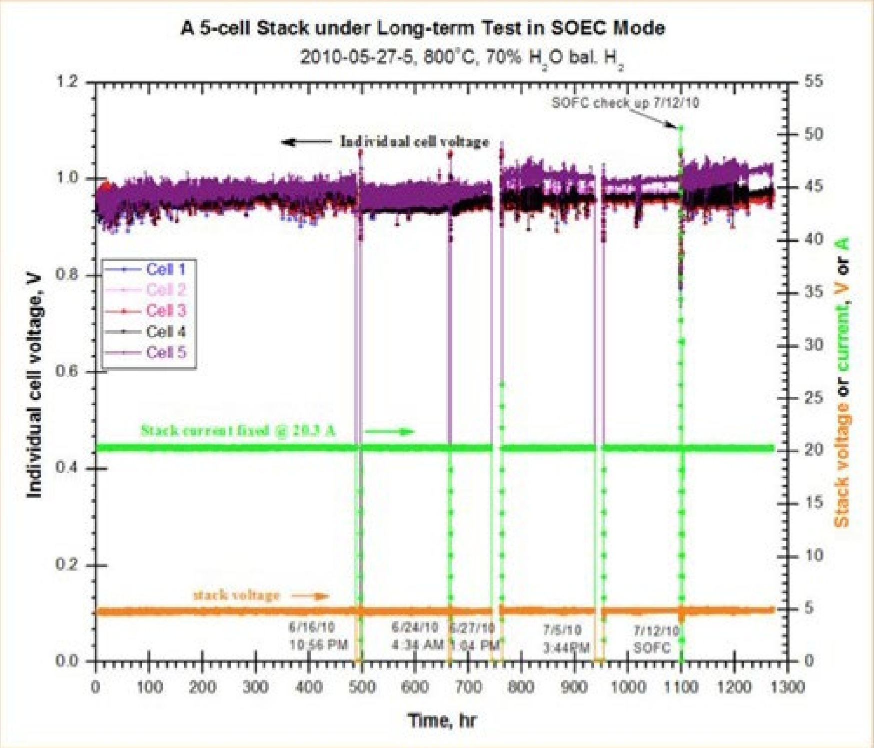
Internally manifolded counter-flow planar stack with anode-supported cells (St. Gobain/FZ Julich)

Subcontractor Testing

MSRI

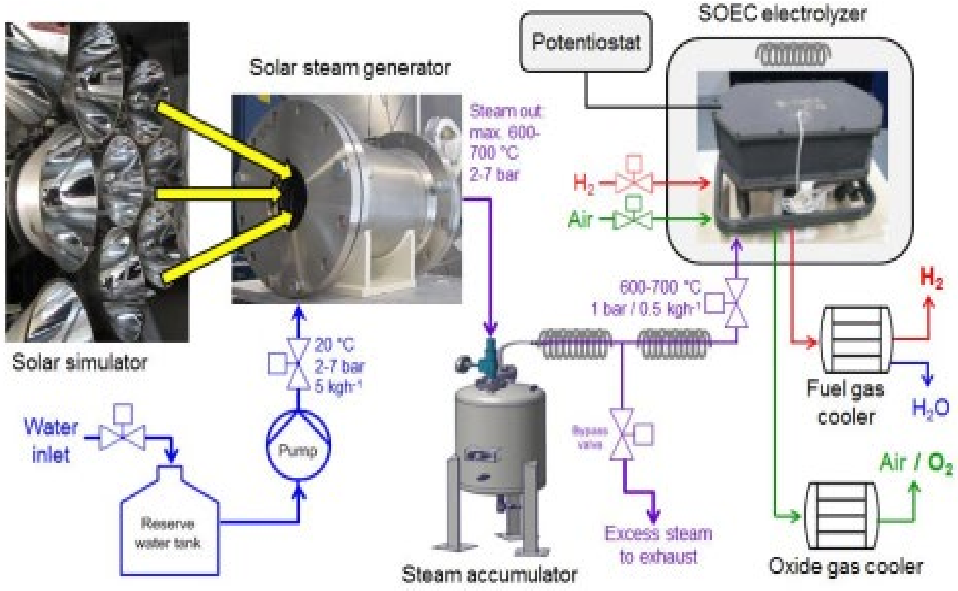
- Small R&D company located in Salt Lake City
- Developer of planar SOFCs and other electrochemical technologies for power and hydrogen production
- INL subcontractor for SOEC development and testing

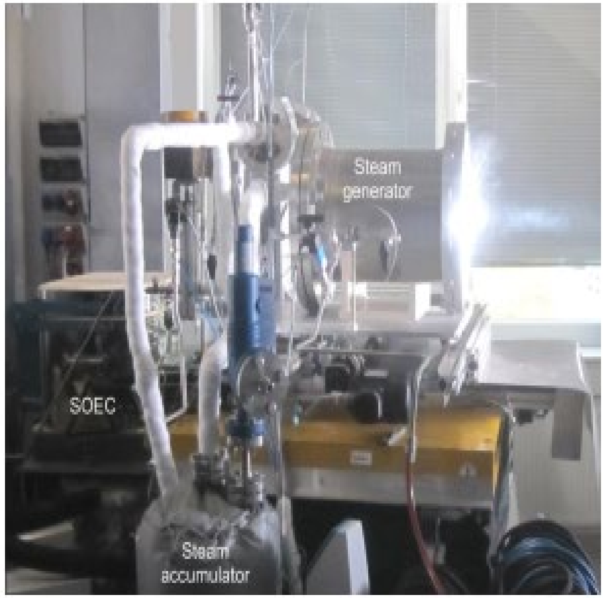
5-cell SOEC stack installed in test stand at MSRI

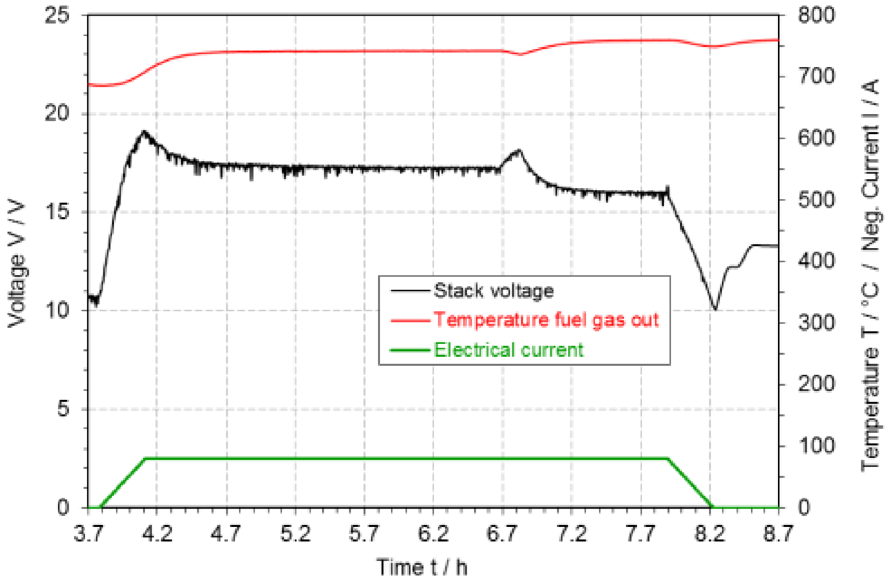


Individual cell voltages, long-term SOEC test, demonstrated <2.5% /khr degradation over 1200 hours

EU Development of HTSE Using Solar Power







Solar hydrogen production at 6.75 L/min

Canadian Focus on Copper-Chlorine Cycle

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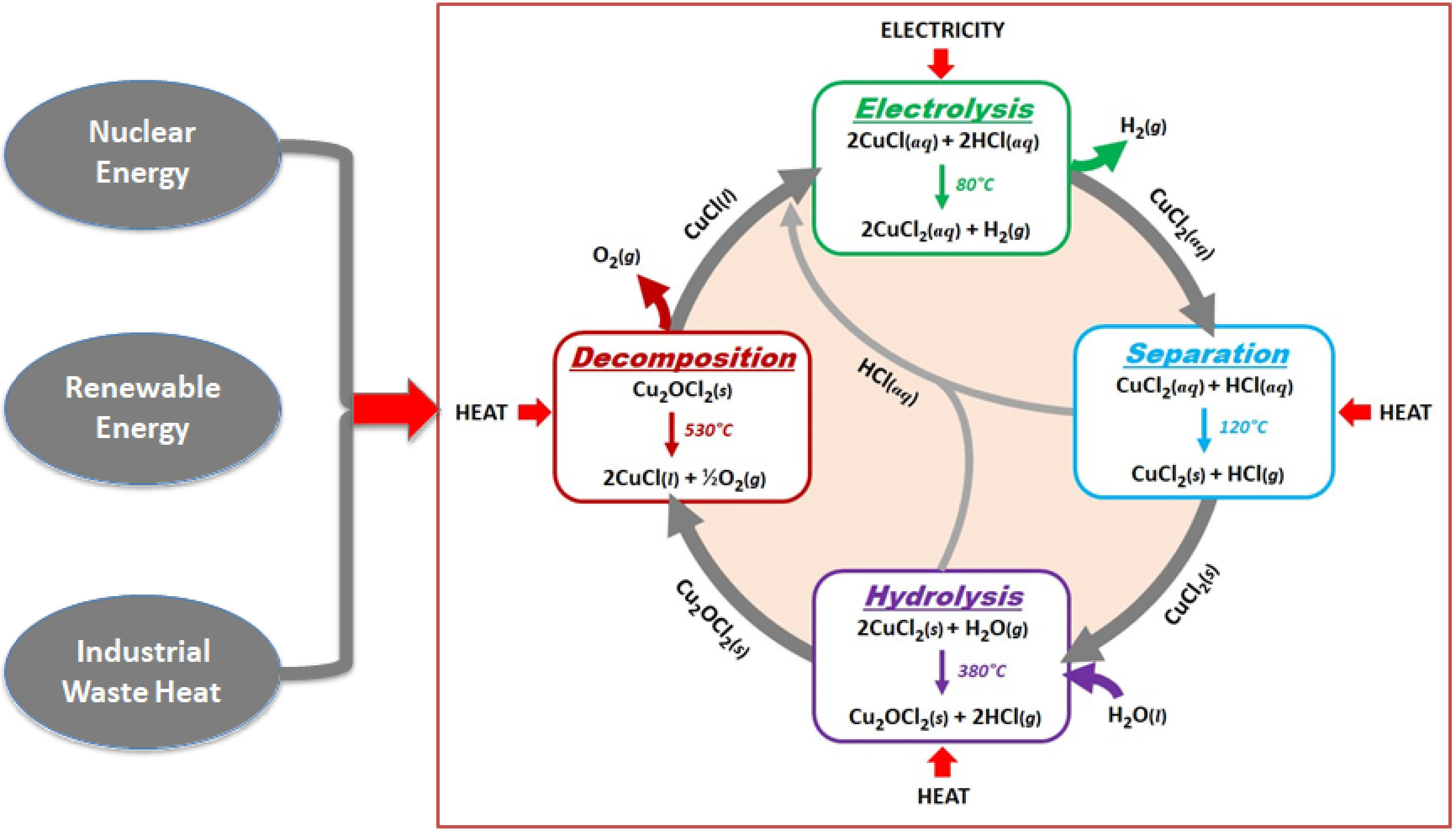
Hybrid Cu-Cl Thermochemical Hydrogen Production



Nuclear Energy

Renewable Energy

Industrial Waste Heat

ELECTRICITY

Electrolysis

$2CuCl(aq) + 2HCl(aq) \xrightarrow{80^\circ C} 2CuCl_2(aq) + H_2(g)$

$H_2(g)$

$CuCl_2(aq)$

Separation

$CuCl_2(aq) + HCl(aq) \xrightarrow{120^\circ C} CuCl_2(s) + HCl(g)$

HEAT

$CuCl_2(s)$

Hydrolysis

$2CuCl_2(s) + H_2O(g) \xrightarrow{380^\circ C} Cu_2OCl_2(s) + 2HCl(g)$

$H_2O(l)$

HEAT

$Cu_2OCl_2(s)$

Decomposition

$Cu_2OCl_2(s) \xrightarrow{530^\circ C} 2CuCl(l) + \frac{1}{2}O_2(g)$

HEAT

$O_2(g)$

$CuCl(l)$

$HCl(aq)$

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

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

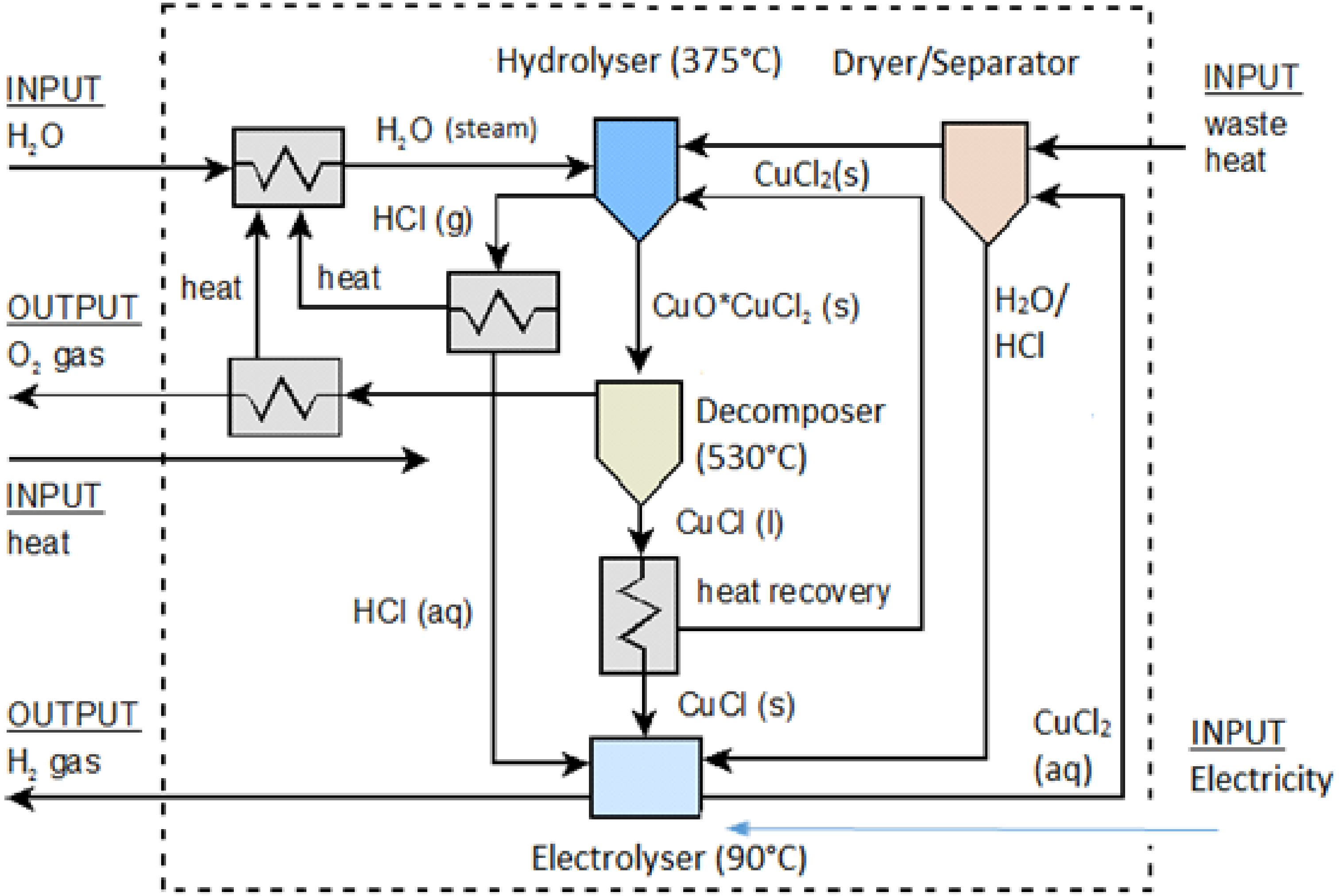


Figure: A schematic of the Copper-Chlorine Cycle for hydrogen production

Simplified MATLAB Model

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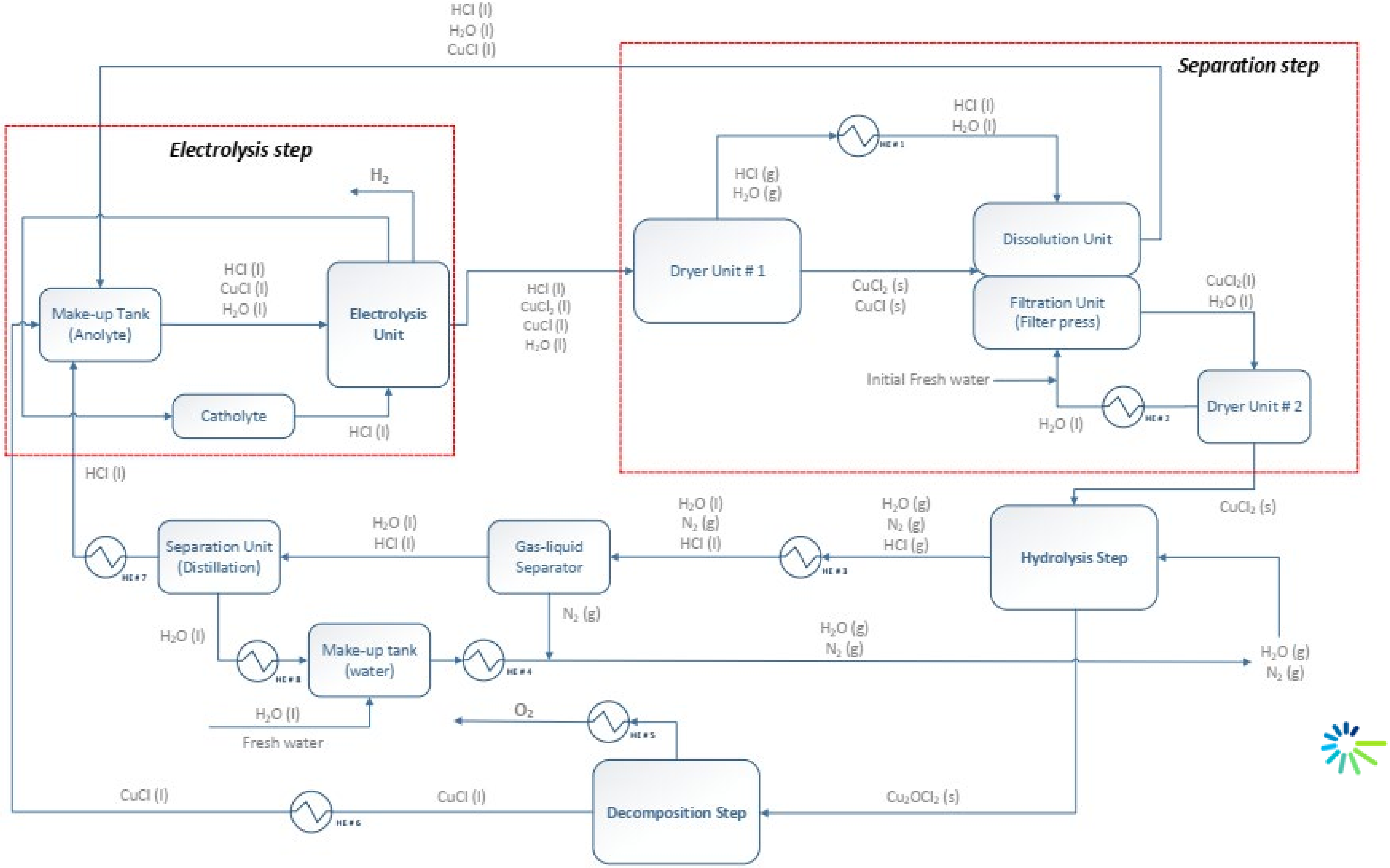

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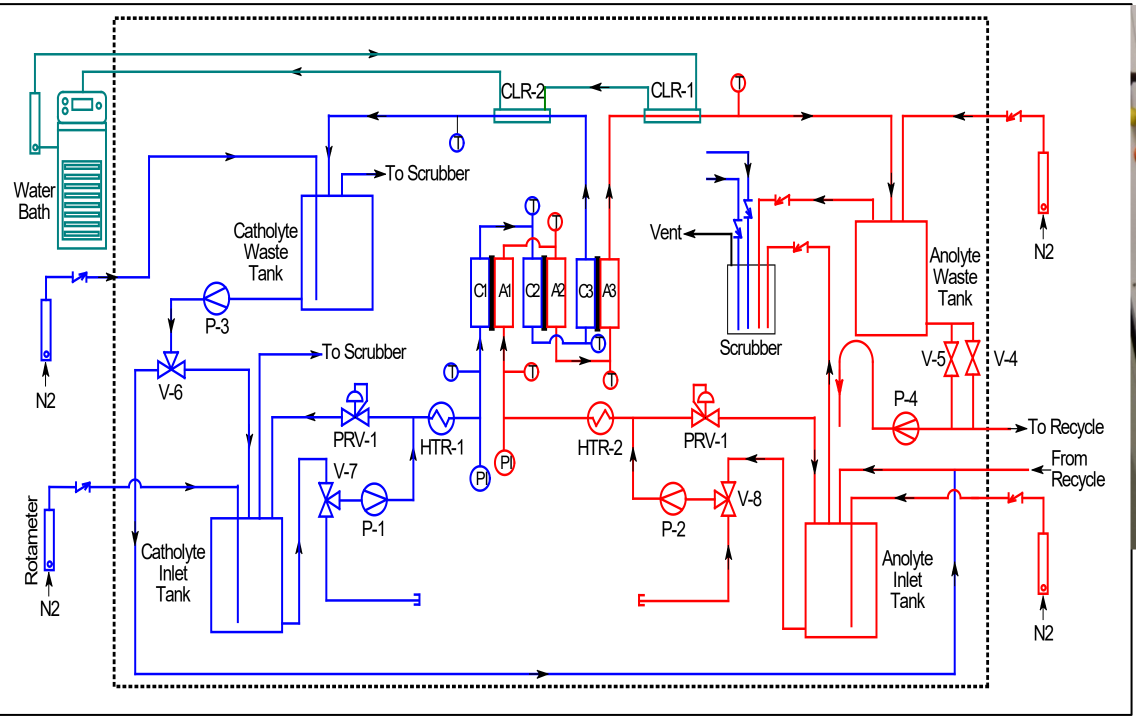
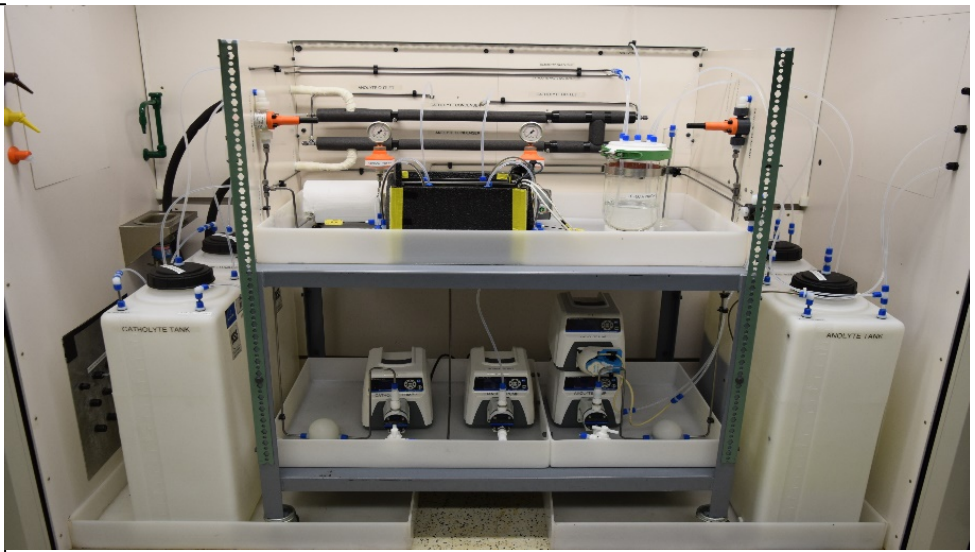
Step 1: Electrolysis Step Development

Originally considered to be the most difficult



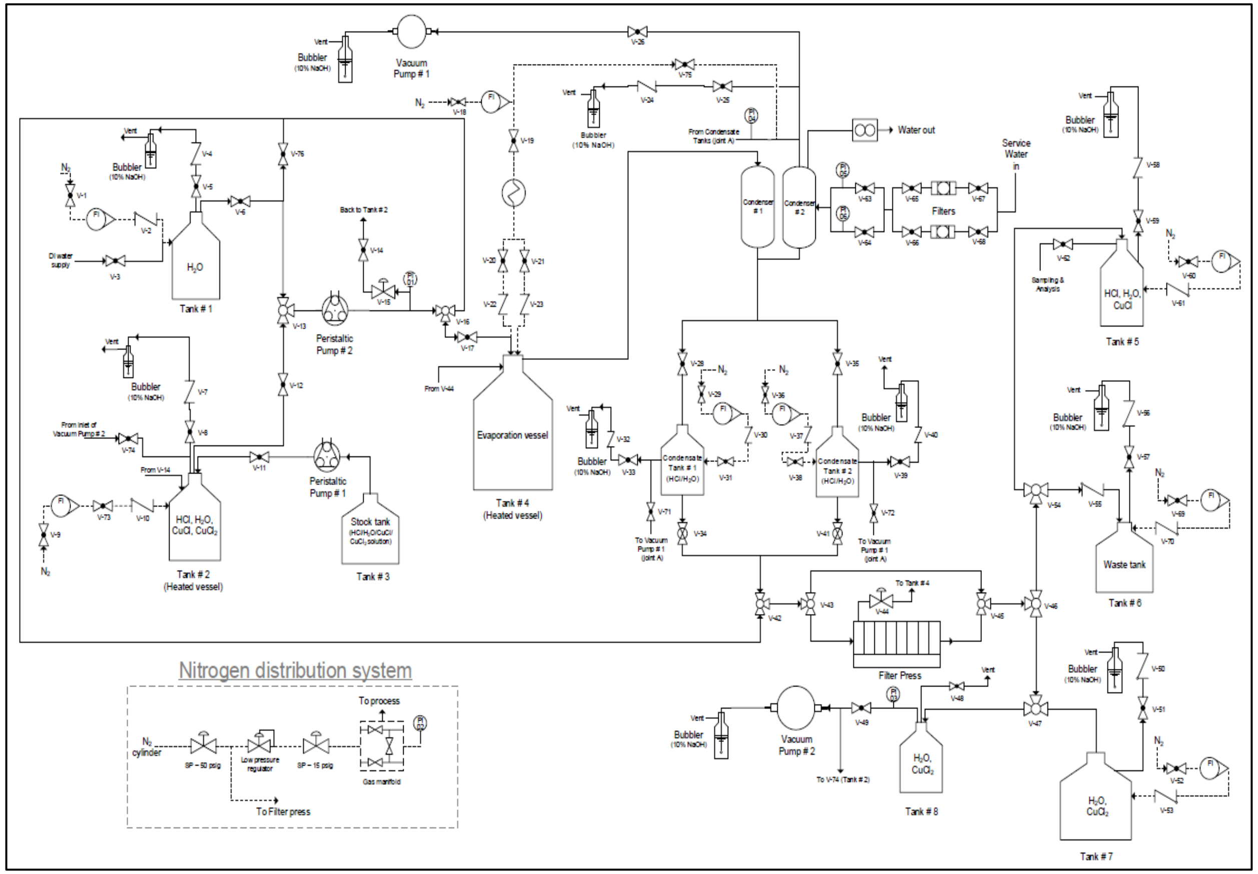
Process Diagram of the Electrolysis Experimental System



Parameter	Target Value	Actual Experimental Value
Hydrogen Production	50 L/h	50 $L \cdot h^{-1}$
Cell Electrode Area	100 cm^2	Three 100 cm^2 in series
HCl Concentration	6.0-8.0 M	8.0 M
Initial CuCl Concentration	0.5-2.0 M	2.0 M
Temperature	70-80 °C	80 °C
Liquid Flow	0.2 $L \cdot min^{-1}$	0.2 $L \cdot min^{-1}$
Current Density	0.4 $A \cdot cm^{-2}$	0.4 $A \cdot cm^{-2}$
Extent of Reaction	50-80%	Up to 75%
Pressure	<103.4 kPa	Anode: <6.9 kPa; Cathode: <34.5 kPa

$$2CuCl(s) + 2HCl(aq) \rightarrow 2CuCl_2(s) + H_2(g)$$

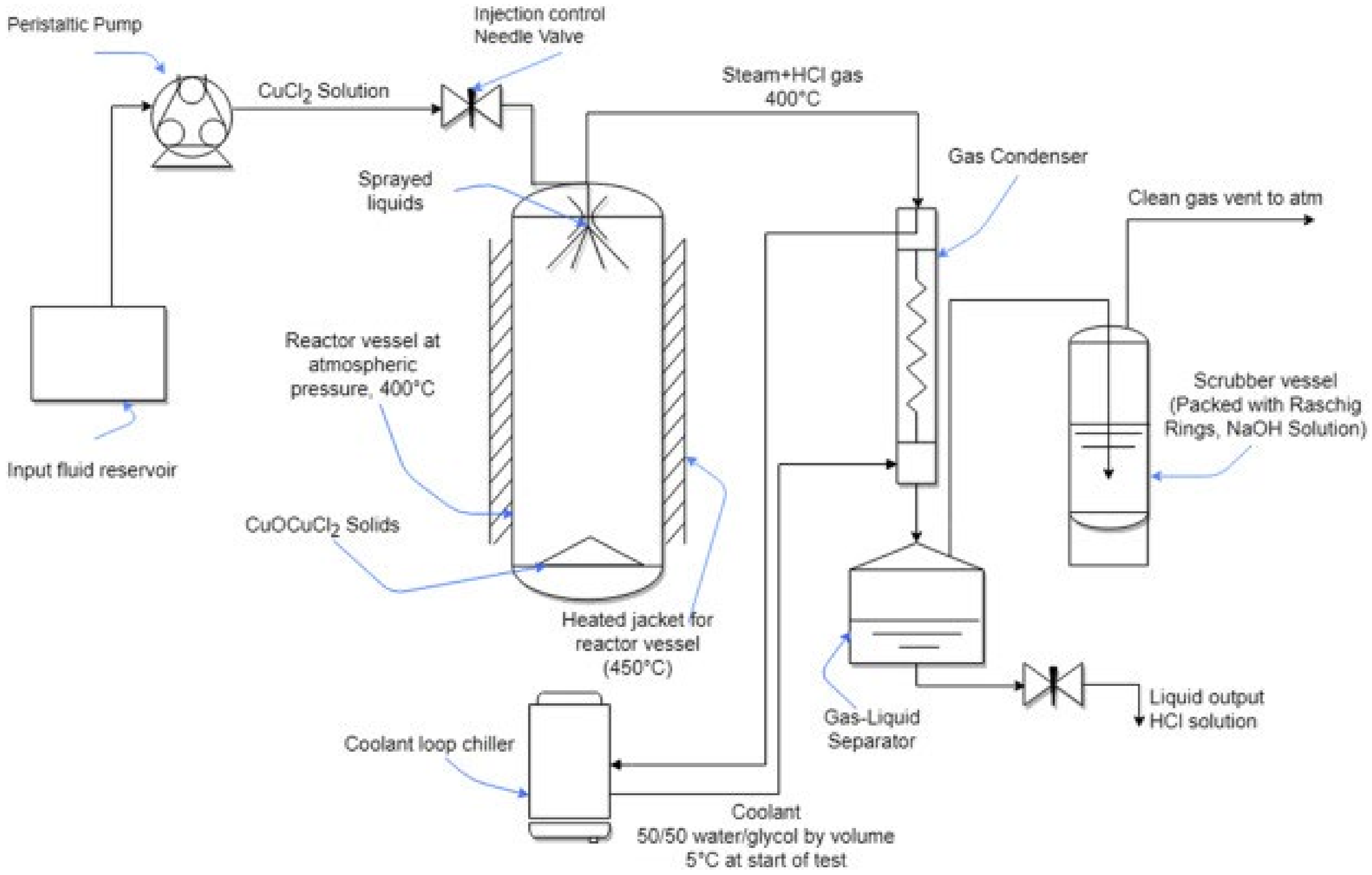
Step 2: $CuCl/CuCl_2/H_2O/HCl$ Separation System

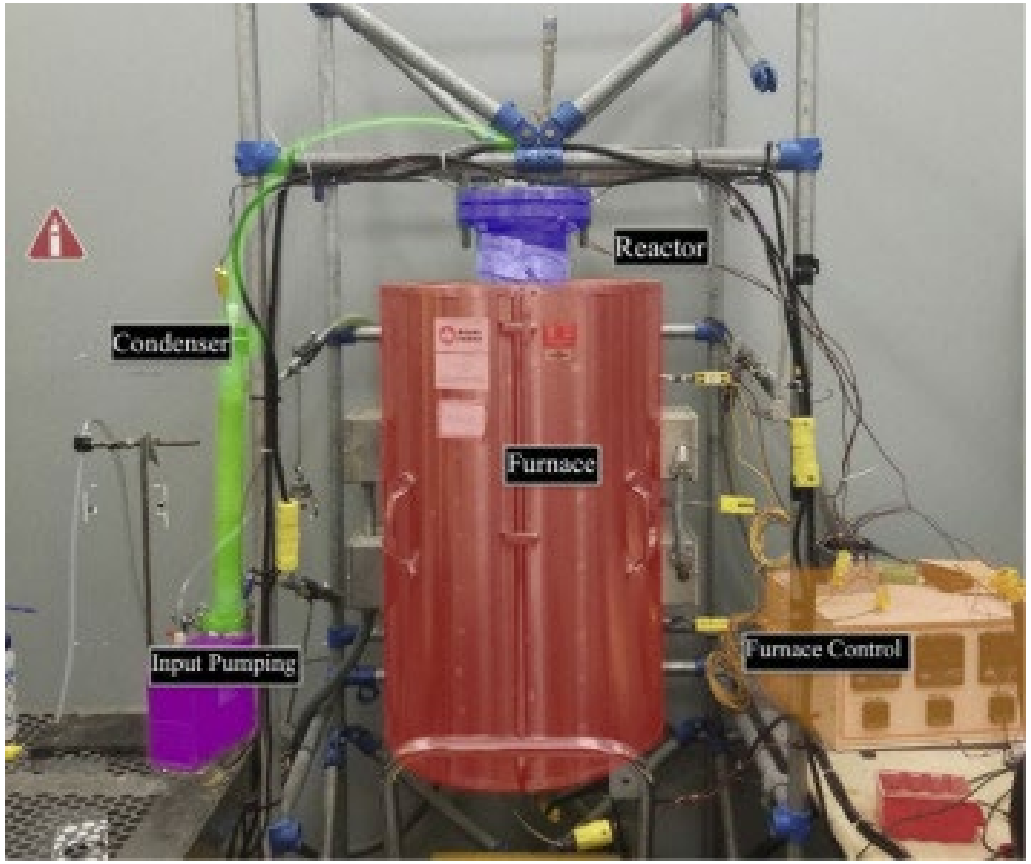


Process Diagram of the $HCl/CuCl/CuCl_2$ Separation System

$$CuCl_2(aq) \rightarrow CuCl_2(s)$$

Step 3: Experimental Study of $CuCl_2$ Hydrolysis

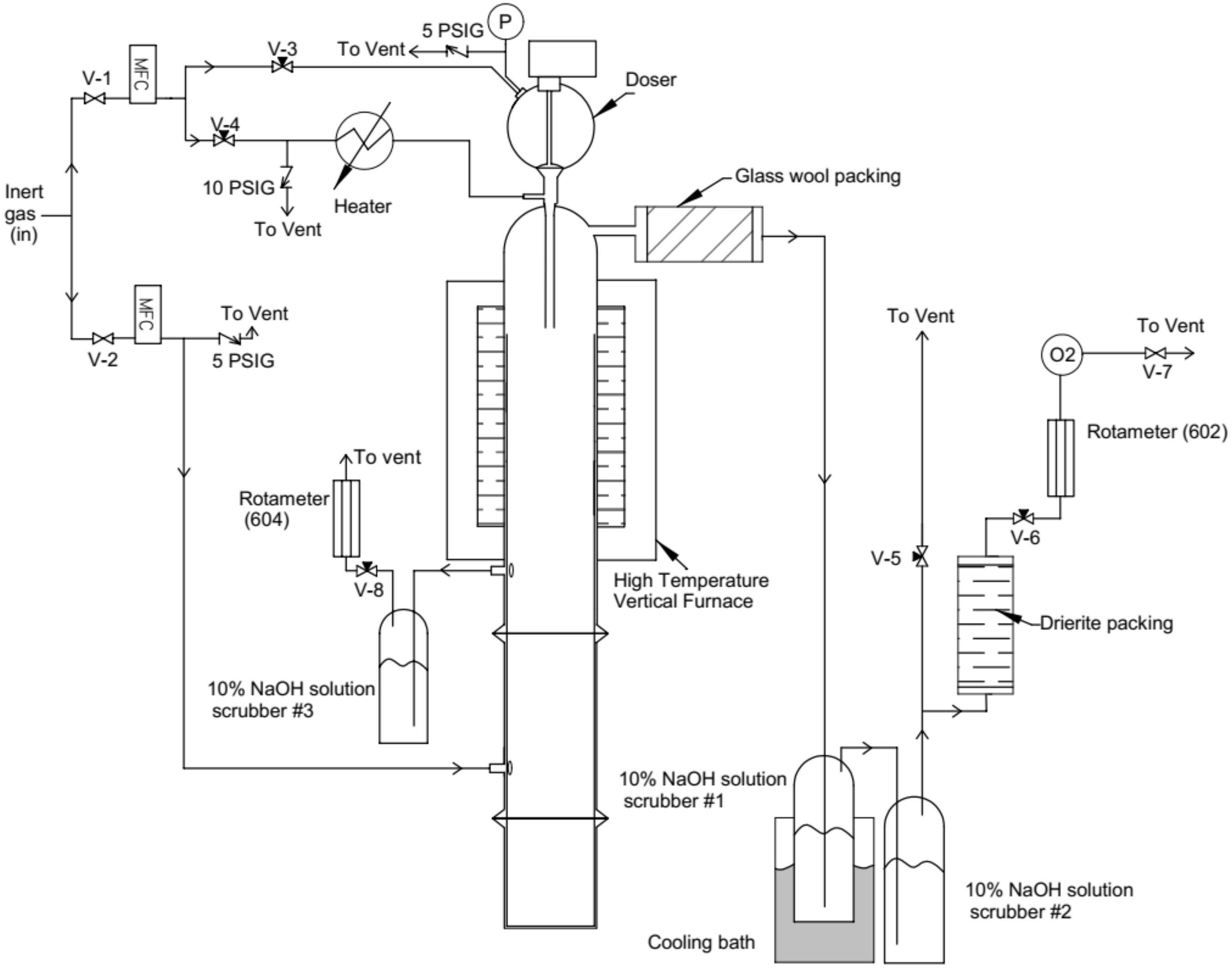




$$2CuCl_2(s) + H_2O(g) \rightarrow Cu_2OCl_2(s) + 2HCl(g)$$

Reference: Kamiel Gabriel, Leonard Finney, Patrick Dolloso, “Preliminary results of integrated hydrolysis reactor in the Cu-Clhydrogen production cycle, International Journal of Hydrogen Energy , December 2018

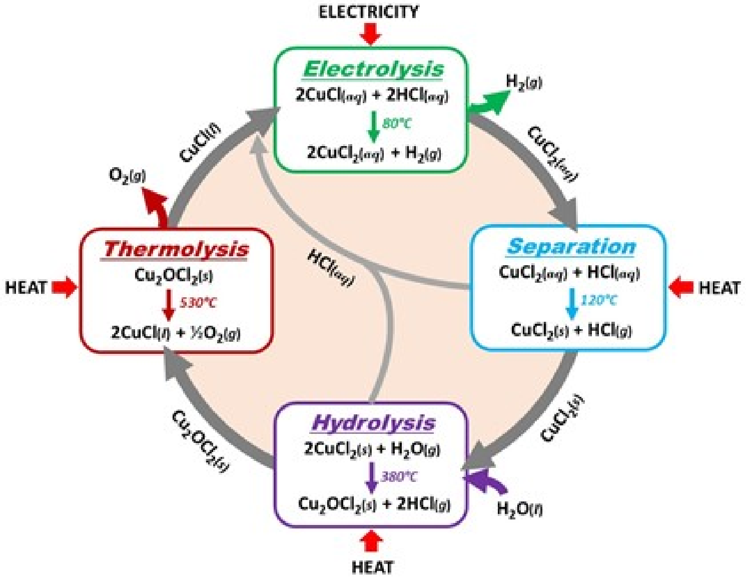
Step 4: Cu_2OCl_2 Decomposition

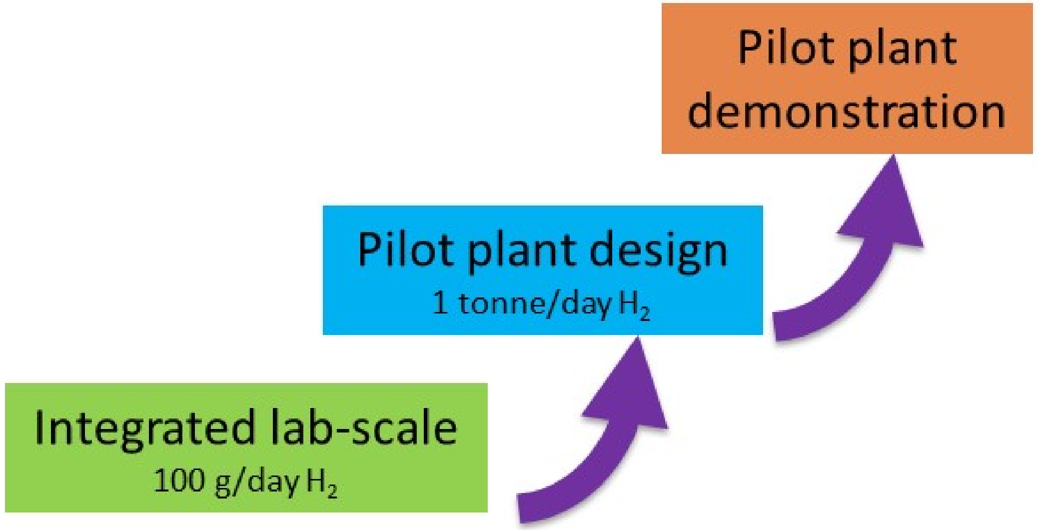


$$Cu_2OCl_2(s) \rightarrow 2CuCl(l) + \frac{1}{2}O_2(g)$$

Semi-Continuous Decomposition System for 50 L/h H_2 production at CNL

Lab-scale Demonstration Plan





Integrated lab-scale
100 g/day H_2

Pilot plant design
1 tonne/day H_2

Pilot plant demonstration

Laboratory Process Development	Pilot Plant Design	Pilot Plant Demonstration
2018-2021	2022-2023	2024-2026

Application Study Collaborations

Commercial Partners

CNL-Govt-Private Investment

→ Location, Energy Sources, H2 Customer

Hybrid-Sulfur Cycle Development

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

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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