Overview of VHTR SSC

43rd Virtual Experts Group Meeting (26 May 2020)
49th Virtual Policy Group Meeting (27 May 2020)
Outline

1. System arrangement
2. SSC members
3. Recent SSC activities
4. VHTR PMBs status
   4-1 Materials PMB
   4-2 Computational Methods, Validation & Benchmarks pPMB
   4-3 Hydrogen Production PMB
   4-4 Fuel and Fuel Cycle PMB
## 1. System arrangement

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2006</td>
<td>• Released VHTR System Research Plan : Version No. 0</td>
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<tr>
<td>30 Nov. 2006</td>
<td>• <strong>VHTR SA Phase I</strong> entered into force for 10 years until 20 Nov. 2016.</td>
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<tr>
<td>July 2009</td>
<td>• Released System Research Plan : Version No. 1</td>
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<td>20 Dec 2012</td>
<td>• Withdrawal of Canada</td>
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<tr>
<td>30 Nov 2016-</td>
<td>• <strong>VHTR SA Phase II</strong> was extended for a period of 10 years <strong>until 30 Nov 2026.</strong></td>
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<td>14 Dec 2017</td>
<td>• Accession of Australian (ANSTO)</td>
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<td>21 Jan 2019</td>
<td>• Accession of UK (BEIS)</td>
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<tr>
<td>Being processed</td>
<td>• Renewal of VHTR System Research Plan : Version No. 2</td>
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3. Recent activities

1) System Overview

  - + CDN in H₂ Production project (need Amend. of PA)
- VHTR SA was extended on 30 Nov 2016 for additional 10 years.
- Most recent meeting: 2-3 October 2019 in Oregon State Univ., US
- VHTR SSC meeting planned for 12-13 May 2020 in Petten, NL, had to be postponed and converted into an online meeting
- Next online SSC will be held on 10 June 2020.

2) Current activities

- Finalizing the SRP renewal (No.2)
- Interaction with PRPP WG for VHTR PRPP White Paper
- Request from WGSAR on fuel qualification of advanced reactors
Examples of Shared VHTR Mat R&D Provide Technical Bases for High Temperature Reactor Design Methods & Construction Rules

- Design rules for use of graphite in gas-cooled reactor cores are being developed and qualified to address loading, irradiation & oxidation effects.

- Alloy 617 was recently approved for high temperature reactor component construction in the ASME Code, using shared contributions from the VHTR Mat PA.

- Fabrication and test method improvements, irradiation effects studies, and codes & standards development for composites are enabling their incorporation in reactor internals & core designs.
Computational Methods, Validation & Benchmarks (provisional) - Update

• Validate tools to assess VHTR performance (Five WPs)
  – Phenomena identification and ranking table (PIRT)
  – Computational fluid dynamics (CFD)
  – Reactor core physics & nuclear data
  – Chemistry and transport
  – Reactor and plant dynamics

• Code validation
  – Benchmark tests
  – Code-to-code comparison
  – Basic phenomena to integrated experiments
  – Supported by HTR-10 and HTR-PM tests or by past reactor data (AVR, THTR and Fort Saint Vrain)
Computational Methods, Validation & Benchmarks (provisional) - Update

• Output
  – HTR-10 in-core temperature measurement experiment has been completed, thermal-hydraulic model is verified
  – PANGU code is developed by INET to perform HTR-10 first criticality calculation
  – Physical & thermal hydraulic design of HTR with higher outlet temperature (from 750 °C to 850 ~ 1000 °C)
  – Safety analysis of coupling HTR to hydrogen production

HTR-10 in-core temperature measurement experiment
Computational Methods, Validation & Benchmarks (provisional) - Update

• Output
  – JAEA performs the burnup analysis benchmark activity using ATR irradiation data using MVP code
  – Development of a system analysis code for transient thermal hydraulic behavior
  – KAERI performed V&V of Fission Product Transport Analysis Codes for plate-out and Tritium behavior
  – Development of coupled code system with 3-D core neutronics code and core thermo-fluid code
Computational Methods, Validation & Benchmarks (provisional) - Update

• Output
  – Advanced gas reactor fuel development and qualification program is carried out by DOE Nuclear Energy
  – HTGR Experimental Validation
    » HTTF at OSU – two LOFC tests done; final data qualification by INL and release as benchmark specification.
    » NSTF at ANL - water-conversion ; 5 tests accepted at single-phase ‘normal’ operation, 1 test accepted at two-phase ‘accident’ conditions.
Canadian developments of the Four-Step Hybrid Copper-Chlorine Cycle for H₂ production have progressed well and a plan in place for its demonstration as per the diagram below.

- Electrolysis system is successfully designed, built, commissioned and tested in laboratory. Electrolyser can produce hydrogen at ~200 g/d, exceeding the target of 100 g/d.

- A separation method based on the solubility of CuCl and CuCl₂ has been successfully established. An experimental rig was constructed, commissioned and tested in laboratory to support H₂ production at 100 g/d.

- Small batch operations have achieved >90% completion of the hydrolysis reaction. Continuous and scalable method is being developed.

- A semi-continuous decomposition reactor system has been built and tested for 100 g/d of H₂.
Complete Copper-Chlorine cycle demonstration plan at CNL

**Diagram:**
- **Electrolysis:** $2\text{CuCl}_2(\text{aq}) + 2\text{HCl}(\text{aq}) \rightarrow \text{H}_2(\text{g}) + 2\text{CuCl}_2(\text{aq})$
- **Thermolysis:** $\text{Cu}_2\text{OCl}_2(s) \rightarrow \text{CuCl}_2(s) + \frac{3}{2}\text{O}_2(\text{g})$
- **Hydrolysis:** $2\text{CuCl}_2(s) + \text{H}_2\text{O}(\text{g}) \rightarrow \text{Cu}_2\text{OCl}_2(s) + 2\text{HCl}(\text{g})$
- **Separation:** $\text{CuCl}_2(\text{aq}) + \text{HCl}(\text{aq}) \rightarrow \text{CuCl}_2(s) + \text{HCl}(\text{g})$

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

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

**Collaborations:**
- Application Study
- Commercial Partners
- CNL-Govt-Private Investment

**Location, Energy Sources, H2 Customer**
Countries Report: R&D progress in 2020

- The key chemical reactors for iodine sulfur process, including sulfuric acid and hydriodic acid decomposers, are being developed. These reactors were designed as a heat exchanger type and as prototype reactors for future scaling-up.

- A high temperature (>900 °C) helium loop is under development, which will supply heat for the performance testing including the hydraulic tests and chemical reaction of the two acids.

- The preliminary design of a pilot-scale iodine sulfur process plant is under development.
• The nuclear hydrogen safety issues, especially on the integration of high temperature gas-cooled reactor and iodine sulfur hydrogen production plant, are under investigation.

• In addition to the IS process development, a development of the hybrid-sulphur process has been initiated in the key technologies relating to SO$_2$ depolarized electrolysis (SDE), and SDE facilities are being established. Some fundamental studies on SDE related to optimization of preparation conditions, semi-empirical models for calculation of polarized voltage, screening of membranes, electrocatalysts, simulation and optimization of the process and stack and balance of plant have been undertaken.
Countries Report : R&D progress in 2020

• High Temperature Steam Electrolysis
• Steam generation units to be coupled to a HTSE unit have been comparatively reviewed and analysed
• A spiral tubular heated steam generator heat by solar radiation has been designed and built (lab scale)
• A pilot plant integrating such steam generator with a SOEC is being test operated using a high flux solar simulator
• Development focus is reaching higher pressures and as low as possible steam mass flow fluctuations
• New mass flow controller is being validated
• Concepts of integrating such device in a plant for renewable hydrogen production have been created
• Sulfur Cycles
• Particles heat exchangers is being built and will be implemented and tested in pilot scale (major contributions by JAEA guest scientist Hiroki Noguchi!)
• Heat particles are integrated with a particle heat exchanger acting at the same time as sulfuric acid decomposer
• Improvement of SO2 monitoring techniques (contributions by H. Noguchi)
• Stability tests of new catalyst compositions (transition metal oxides)
• Corrosion resistance tests of transparent materials
• Evaluation of overall process of sulfur cycle for hydrogen production and heat storage
Recent efforts by CEA have focused on optimization of solid oxide cells and stacks for both electrolysis and fuel-cell reversible modes of operation. When integrated with nuclear systems, the ability to switch to low power fuel cell mode helps to limit cycling of the stacks (to minimize degradation) for electrolysis operation.

Some of the recent findings are:
- Thicker oxygen electrode (7 µm -> thicker) led to enhanced performance.
- Thinner barrier layer (below µm scale) led to enhanced performance.
- Long-term durability in SOEC mode.
  » Initial degradation too high.
  » Acceptable degradation after stabilization period.

CEA is also conducting preliminary studies on Small Modular Reactor/HTSE coupling.
2nd generation cell @85%RU, 0.6A/cm² in SOFC mode in dry H₂ and 1.2A/cm² in SOEC mode with 10% H₂ in steam
Following the long-term continuous H₂ production test conducted in 2019 (150 h @ 30 L/h H₂ production), the facility is undergoing inspection of components to acquire corrosion data to understand longer term operational impacts.

Development of an automated control system to acquire ranges of process operational parameters under larger H₂ production conditions is underway.

Assessments have also been conducted on HTGR cogeneration system for H₂ and electricity production; a 600 MWt HTGR reactor is capable of producing 6.2 ton/h H₂ and 87 MWe.

It is anticipated that HTGR coupled to H₂ production system will be installed in 2040 to meet the demand for H₂.
Continuous hydrogen production test facility

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

**Facility**
- $\text{H}_2$ production: **100 NL/h-scale**
- Construction year: **2014**

**Component materials**
- **Select the industrial materials**
  - **Liquid phase**
    - SiC ceramic
    - Graphite (impervious)
    - Fluororesin-lined steel
    - Glass lined-steel
  - **Gaseous phase**
    - Ni base alloy
    - JIS SUS316

(Vessels, Sheath for thermocouple, etc.)
Countries Report : R&D progress in 2020

- Earlier focus on Sulphur-Iodine process developments
- Techno-Economic Analyses of H₂ Production Processes, including Steam Methane Reforming, coupled to HTGR
350 MWth Cogeneration PFD with HTSE H₂ production

H₂ production rate: 34,854 Nm³/h
Electric generation: 106.8 MWₑ (Brayton)
Electrical energy demand in HTSE process: 106.8 MWₑ

H₂ production rate: 42,104 Nm³/h
Electric generation: 129 MWₑ (Brayton)
Electrical energy demand in HTSE process: 129 MWₑ
Countries Report : R&D progress in 2020

Coupling of Nuclear with High Temperature Electrolysis for Hydrogen Production

- Deploy, integrate, and operate flexible 25 – 250 kW HTE test facilities in the INL Dynamic Energy Transport and Integration Laboratory (DETAIL)
  - Promote wider use of carbon-free renewable and nuclear energy in coordinated configurations
  - Demonstrate and characterize simultaneous coordinated multi-directional transient distribution of electricity and heat for multiple industrial process heat applications
  - Characterize system performance under long-term and flexible operating conditions
  - Simulate broader systems using real-time digital simulators with hardware-in-the-loop configurations
  - Document HTE operational and performance characteristics in a grid-dynamic environment
- Evaluate the potential of HTE systems to achieve efficient, low-cost hydrogen production with optimized operational profiles designed to take advantage of intermittent low-cost electricity and integrated process heat
  - Document overall stack performance, degradation rates, and mechanisms
  - Document performance characteristics associated with intermittent HTE operations
  - Investigate the impacts of grid instability on HTE operations
  - Demonstrate the utility of HTE thermal integration with co-located systems
25 kW HTE Test Facility

- Completed Installation and Commissioning of 25 kW HTE Test Facility
- Completed Initial Testing at the 5 kW scale; long-term operation over 1000 hours

stack installation
INL System Integration Laboratory
High Temperature Steam Electrolysis (HTSE)
Thermal Energy Distribution System
Microreactor Test Bed (nonnuclear)