Very High Temperature Reactor

Collaborative R&D, Demo Projects, Market

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on behalf of the
GIF VHTR System Steering Committee
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Outline

1. System overview
2. Projects and Highlights
   - Materials
   - Fuel and Fuel Cycle
   - Hydrogen Production
   - Computational Methods, Validation & Benchmarks
3. Future collaborative projects
4. Related international activities
5. Main potential HTR vendors
6. Market Studies and Economics
7. Wrap-up and Announcement of HTR 2018
1. System Overview

- **7 Signatories:** CH, EU, FR, JP, KR, US, CN
  + CDN in $H_2$ Production project
  + Australia in Materials project

- Next SSC Meeting:
  17-19 April 2018 in Sydney

**Active projects:**

1. **Materials**
2. **Fuel and Fuel Cycle**
3. **Hydrogen Production**
4. **Computational Methods, Validation & Benchmarking**
   (approved by SSC, ready for signature)
2.1 Materials

Objectives:
• Development and qualification of materials
  • Irradiation-induced and/or environmental and/or time-dependent material failure
  • ≤ 950°C: existing materials
  • ≤ 1 000°C (incl. safe operation under off-normal conditions and involving corrosive process fluids): new materials with development and qualification needs
• Design codes and standards
• Manufacturing methodologies
• Improved multi-scale modelling to support inelastic FEM analyses
• High-temperature heat exchangers and steam generators

3 Material Categories and corresponding WG:
  1. graphite for core structures, fuel matrix, etc.;
  2. very/medium-high-temperature metals;
  3. ceramics and composites.

Materials handbook: developed and used to store and manage VHTR data, facilitate international R&D co-ordination and support modelling to predict damage and lifetime. Thousands of data sets uploaded.
2.1 Materials

• Two scheduled tracks at the GIF Symposium in October 2018 may include structural materials activities that crosscut multiple reactor systems, including advanced manufacturing methods

• A dedicated crosscutting session of VHTR Materials PMB meeting to be held in conjunction with the GIF Symposium will include participation from other structural materials related PMBs/SSCs
  – SFR PMB on Advanced Fuel
  – MSR Provisional SSC
  – LFR Provisional SSC
  – GFR SSC
  – SCWR PMB on Chemistry & Materials had conflicts/absent

• A GIF Task Group to examine overall materials crosscutting needs to be formed
Irradiation effects on Oxidation-resistant Graphite (1/3)

1.6: Graphite Irradiation Effects

**Objectives**
- To clarify irradiation effects on oxidation-resistant graphite

**Collaboration**
- JAEA: Analysis, Evaluation
- INP - Kazakhstan: Irradiation using WWR-K reactor
- TovoTanso, IBIDEN, TOKAI CARBON, Nippon Techno-Carbon: Supply graphite specimen

Under the framework of ISTC partner project

**R&D Items**
- Evaluation of irradiation effects and oxidation behaviour
  - Integrity of SiC surface coating
  - Oxidation resistant performance

**Present Status**
- Irradiation test by WWR-K reactor: completed 200 days, 1200°C
- Capsule dismantling: completed specimens were extracted from 2 capsules
- First PIE at INP: completed dimension, weight, surface condition
- Second PIE at INP: completed Oxidation test for irradiated samples
2.2 Fuel and Fuel Cycle

- Several fuel **irradiation tests** completed, PIE and safety testing ongoing (US, EU+CN, KR)

- **Data analysis from irradiation and PIE**: fission product balance, safety testing, destructive analysis (deconsolidation-leach-burn-leach, gamma counting of individual particles, finding and analyzing particles with failed SiC, non-destructive particle x-ray analysis, particle microanalysis)

- **Property measurements of irradiated coatings** (EU, FR, JA, KR)

- Sample preparation for **Leach-Burn-Leach** round robin (US, KR, CN)

![X-rays of simulated coating defects](image)
FFC Progress: USA

- **AGR-2** Completing analysis of fission product inventory in the graphite fuel holders, study of irradiated compact cross-sections. Destructive compact examination and safety tests in progress.

- **AGR-3/4** PIE is currently in progress

- **AGR-5/6/7** is the final fuel qualification irradiation and performance margin test. Fuel fabrication completed at BWXT

- Progress has been made on the round robin experiment to benchmark the Leach-Burn-Leach (LBL) process

- Conceptual design for an in-cell furnace for heating fuel specimens in gases containing oxygen and moisture completed

![Image of fuel pellets and graph showing fractional release vs. elapsed time with labels for Sr-90 and Eu-154 isotope concentrations over different temperature ranges. The graph indicates that Sr-90 shows a higher fractional release with increasing temperature compared to Eu-154. There is a legend indicating isotope concentrations and a note on average measured diameter: 8.72 mm, standard deviation: 0.236 mm, as-fabricated diameter: 12.28 mm, initial - measured = 12.28 - 8.72 = 3.56 mm.]

![Image of a fuel specimen showing a close-up of a fuel pellet with a label reading Frame 75. The fuel pellet appears to have a layered structure with visible circular patterns, possibly indicative of fuel rod composition or an examination technique. There is also an inset detailing the fuel specimen's characteristics, such as diameter measurements and material composition.]
FFC Progress: China

- Two INET pebbles irradiated in Europe were transferred from NRG to JRC in April 2016, together with 5 irradiated pebbles for HTR-PM. PIE on HFR-EU1 will be performed in 2018. (HTR-PM irradiation and safety testing performed between China and EU as a bilateral contract.)
- Hot cells and key equipment was designed. Construction started in October 2017.
- R&D on coated particles with UCO kernel and ZrC coating ongoing. First stage on UCO kernel manufacturing completed.
2.3 H₂ Production

Objectives:
Was original driver for VHTR development. After initial work by several signatories, SI and HTSE identified as most promising.

- Feasibility, optimization, efficiency and economics at small and large scale
- Performance and optimization in test loops, from lab scale through pilot and demo scale
- Component development (e.g. advanced process heat exchangers)
- Coupling technology with the nuclear reactor incl. risk analysis of potential interactions between nuclear and non-nuclear systems
- Technical and economic feasibility in dedicated or cogen mode
- Reduction of process temperature to gain compatibility with other GIF concepts
2.3 H₂ Production

- **Signatories:** CDN, EU, FR, US, KR, JA + CN
- Most recent PMB meeting Cologne, Germany, 17-19 October 2017
- **Processes:**
  - Sulfur/iodine cycle: KR, JA, CN
  - High-Temperature Steam Electrolysis: FR, US, EU, CN, CDN
  - Hybrid copper-chloride cycle: CDN
  - Hybrid sulfur cycle: ?
- **Output:**
  - Use of HTTR as heat source will enhance credibility of nuclear H₂ production;
  - Good: Contributions from non-nuclear projects
  - Project successfully re-invigorated, more collaboration
2.3 H₂ Production

- **Canada:** Copper-Chlorine cycle for demonstration over the next 3 to 5 years. Collaboration with University of Ontario.
- **US:** New INL Project DETAIL (Dynamic Energy Transport and Integration Laboratory): dynamic coupling of nuclear, renewables, electrolyzers (PEM & HT), and industrial processes to maximize renewable penetration, revenue, grid stability, etc.
- **Japan:** Continuous H₂ production tests on the IS process engineering facility
- **Korea:** 50 l/h scale SI Integration Test (2014), Modification of Sec I & Sec III and 50 l/h scale SI Integration Reproducibility
- **Europe:** HTSE using solar energy; use of H₂ for Hybrid Energy Systems;
- **China (observer):** Safety of SI process, development of prototype acid decomposers for H₂SO₄ and HI;
2.3 H₂ Production

- Several facilities combining 3 elementary processes to a thermo-chemical cycle process were built and operated (JA, CN)
- Continuous, stable operation at 20-60 l/h for almost 4 days
- Progress in materials, components, optimization of elementary processes, process control, safety, system integration, cost evaluation etc.
2.4 Computational Methods, Validation & Benchmarking

Objectives:

- Tools to assess reactor performance in normal, upset and accident conditions.
  - Construction of a phenomena identification and ranking table
  - Computational fluid dynamics
  - Reactor core physics and 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 (e.g. AVR, THTR and Fort Saint-Vrain)

-> eliminate unnecessary design conservatisms and improve construction cost estimates
2.4 Computational Methods, Validation & Benchmarking

Output:
- HTR-10 in-core temperature measurement ongoing
- CN considers input from one or several of 16 HTR-PM engineering test facilities (useful for V&V of codes and methods)
- KR works on experimental validation of hybrid air/water RCCS (safety relevant)
- US has constructed test facilities (HTTF, NSTF, MIR…) to validate codes

Productive upfront collaboration:
- Good: several signatories already active and will contribute results as BPI
3. Future Collaborative R&D Topics

• Targeted towards medium-term demonstration and long-term performance.

• Some topics suitable for collaboration within GIF, others more for IAEA or OECD/NEA or bilateral collaboration frameworks.

• Headlines (cf. GIF R&D Outlook):

  1. Materials (advanced), Components and Supply Chain
  2. Design, System Integration and Cost Reduction
  3. Safety Demonstration and Licensing (IAEA CRP, OECD/NEA GSAR)
  4. Fuel, (advanced) Fuel Cycle, and Waste Minimization
  5. Coupling to Cogeneration Applications

➔ Ample opportunities for further fruitful cooperation on HTGR, VHTR and process heat applications
4. Related international activities

**PRIME**

- Joint effort of NC2I, NGNP IA, JAEA and KAERI for demo
- Workshops in Paris, Washington, Piketon, Brussels, Las Vegas, Warsaw
- Related EU project kicked off in Sept 2017 (GEMINI+), focus on Poland; expected results similar to various NGNP business plans (Wyoming, Kentucky), synergies with INL project DETAIL, next meeting on 13 April 2018 in Prague;
- Modular design to meet common needs:
  - similar components
  - e.g. 165 MWth pure steam to meet industry requirements in Poland

**UK Department for Business, Energy & Industrial Strategy**

SMR Techno-Economical Assessment and £ 250 million SMR call (participation of GEMINI);

LWR and HTGR with high TRL are being considered for medium-term deployment;

Next steps: financing of approx. 10 feasibility studies, thereafter technology development for shortlisted designs (£ 10 million each)
5. Main potential HTR Vendors

All contacted to complete GIF SIAP questionnaire
Details received from INET, AREVA, JAEA

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNNC</td>
<td><strong>HTR-PM</strong>, 250 MWth / HTR-PM600, 600 MWe, <strong>pebble bed</strong>, electricity</td>
</tr>
<tr>
<td>(NIA/NC2I/KNHA)</td>
<td>NHSS, 350 MWth (200 – 625 MWth), block, cogen, <a href="http://www-ngnpalliance.org">www.ngnpalliance.org</a></td>
</tr>
<tr>
<td>X-Energy</td>
<td>Xe-100, 200 MWth, <strong>pebble bed</strong>, <a href="https://www.x-energy.com/">https://www.x-energy.com/</a></td>
</tr>
<tr>
<td>HTMR</td>
<td>HTMR-100, 100 MWth, <strong>pebble bed</strong>, <a href="http://www-thorium100.com/HTMR-100%20Reactor.php">http://www.thorium100.com/HTMR-100%20Reactor.php</a></td>
</tr>
<tr>
<td>Starcore Nuclear</td>
<td>36 MWth + 20 MWe, cogen, static <strong>pebble bed</strong> (2013, <a href="http://starcnarepower.com">http://starcnarepower.com</a>), now block (<a href="http://starcnareuclear.ca">http://starcnareuclear.ca</a>)</td>
</tr>
<tr>
<td>JAEA</td>
<td>GTHTR-300, 600 MWth, block, electricity, cogen, H₂, <a href="http://httr.jaea-go.jp/eng/">http://httr.jaea.go.jp/eng/</a></td>
</tr>
<tr>
<td>U Battery cons.</td>
<td>U Battery, 10 MWth, block, cogen, <a href="https://www-u-battery.com/what-is-u-battery">https://www.u-battery.com/what-is-u-battery</a></td>
</tr>
</tbody>
</table>
6. Market Studies and Economics

Very significant information compiled and analyzed by:

- IAEA TECDOCS, Technical Meetings etc.
- OECD/NEA publications (cf. slides by Marc Deffrennes)
- German HTR Program (PNP for coal refining) in 1970-1989, especially after oil crises
- South Africa: Techno-economics of use of process heat from HTGR for CTL

Focus here on (process heat, $H_2$, electricity):

- EU: NC2I (MICANET, Europairs, ARCHER, NC2I-R, GEMINI+)
- US/Canada: NIA (Wyoming, Kentucky, Texas, oil sand recovery)
- China: electricity and process heat
- South Korea: process heat and $H_2$
- cf. summary at GIF PG meeting October 2017
6. Market Studies and Economics

<table>
<thead>
<tr>
<th>Region</th>
<th>Plug-in market</th>
<th>Total market</th>
<th>GDP 2011 (approx.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>~ 800 TWh/y (EUROPAIRS)</td>
<td>~ 3,000 TWh/y (EUROPAIRS)</td>
<td>17,000 bn€ / 25% of world</td>
</tr>
<tr>
<td>USA</td>
<td>~ 1,100 TWh/y (MPR Associates)</td>
<td>~ 3,600 TWh/y (MPR Associates)</td>
<td>15,000 bn€ / 22% of world</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td>1,000 – 1,400 TWh/y (est.)</td>
<td>5,900 bn€ / 8% of world</td>
</tr>
<tr>
<td>China</td>
<td></td>
<td>1,200 – 1,700 TWh/y (est.)</td>
<td>7,000 bn€ / 10% of world</td>
</tr>
<tr>
<td>India</td>
<td></td>
<td>300 – 500 TWh/y (est.)</td>
<td>2,000 bn€ / 3% of world</td>
</tr>
<tr>
<td>Russia</td>
<td></td>
<td>300 – 500 TWh/y (est.)</td>
<td>2,000 bn€ / 3% of world</td>
</tr>
<tr>
<td>World total</td>
<td>3,000 – 5,000 TWh/y</td>
<td>11,000 – 16,000 TWh/y</td>
<td>69,000 bn€</td>
</tr>
</tbody>
</table>

Not a niche market but room for several hundred reactors!

Source: Bredimas
6. Market Size in EU28

Polygeneration

Plug-in | Pre-heating | Extended heat market
--- | --- | ---
784 TWh/y | 117 TWh/y | 361 TWh/y | 1,830 TWh/y

= 89.5 GWth

Market of conventional cogeneration today

Potential short-term market for nuclear cogeneration

Market difficult to supply in the short and medium term
7. Wrap-up

- GIF VHTR projects share expertise and infrastructure and progress well
- FFC and MAT projects are in a productive harvesting phase
- HP and CMVB projects were successfully revitalized (increased interest from energy system integration, improved personal commitments)
- Excellent collaborative achievements confirm usefulness of GIF
- Several countries active in VHTR (several companies, new projects)
  - Safety, high efficiency, process heat applications (steam, H₂)
  - PRIME [Poly-generation Reactor with Inherent safety, Modularity and Economic competitiveness (EU,US,JA,KOR)], Test Reactor and Demo in PL BATAN (Indonesia), StarCore Nuclear (Canada), X-Energy (US)
  - HTTR (Japan) accelerated regulator OK would be extremely positive
  - HTR-10 (China) is running
  - HTR-PM (China) start-up at end-2018
- Synergistic cooperation with IAEA and OECD/NEA
Warsaw (Novotel), 8-10 October 2018

More than 100 papers received

- Track-1: National Research Programs and Industrial Projects
- Track-2: Industrial Applications and Markets
- Track-3: Fuel and Waste
- Track-4: Materials, Components and Manufacturing
- Track-5: Reactor Physics Analysis
- Track-6: Computer Codes and Analysis
- Track-7: Development, Design and Engineering
- Track-8: Safety and Licensing