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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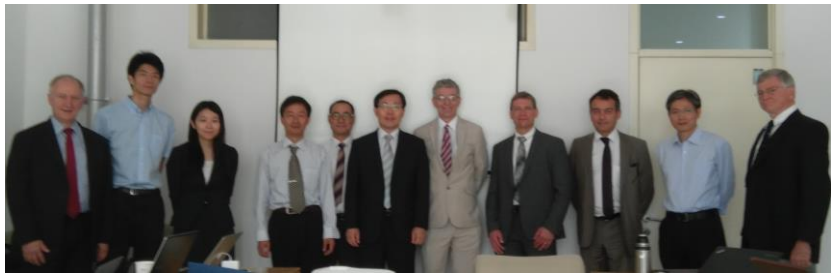
Outline

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



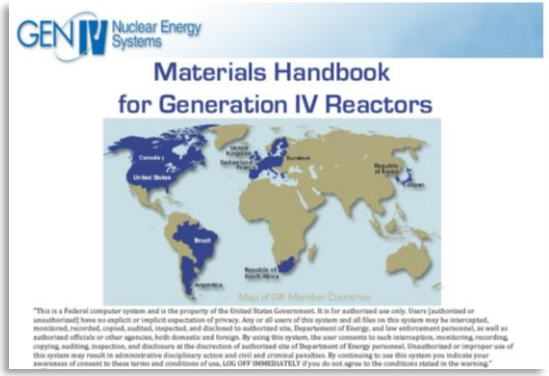
Active projects:

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



https://gen4www.ornl.gov

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/was absent
- A GIF Task Group to examine overall materials crosscutting needs to be formed

Example from VHTR Materials PMB Graphite Working Group

Irradiation effects on Oxidation-resistant Graphite(1/3)

1.6: Graphite Irradiation Effects

JAEA

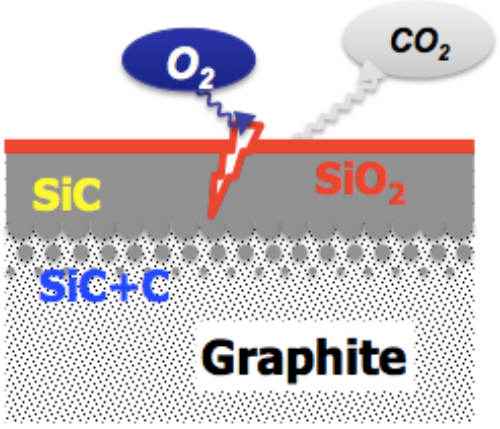
- ***Objectives***
  - *To clarify irradiation effects on oxidation-resistant graphite*

Collaboration

- *JAEA : Analysis, Evaluation*
- *INP - Kazakhstan : Irradiation using WWR-K reactor*
- *ToyoTanso, 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*

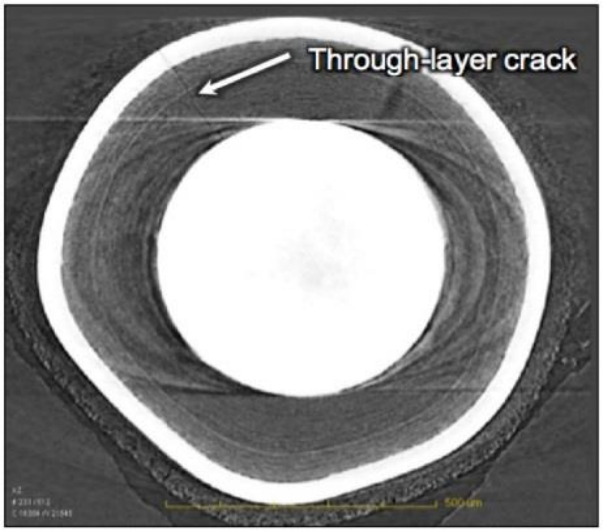


Present Status

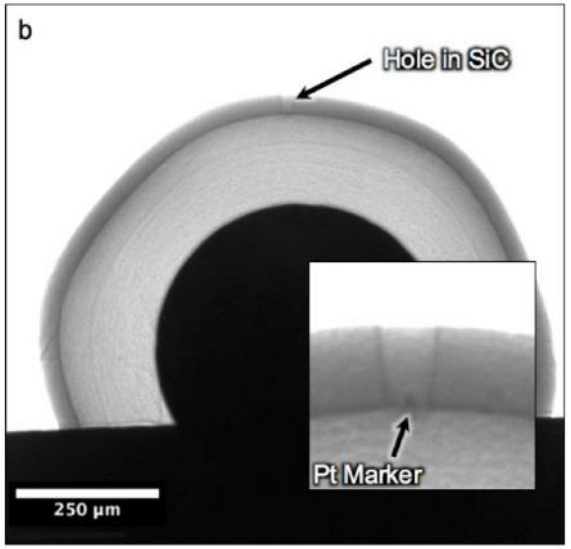
- *Irradiation test by WWR-K reactor: completed*
  200days, 1200C
- *Capsule dismantling: completed*
  specimens were extracted from 2 capsules
- *First PIE at INP: completed*
  dimension, weight, surface condition
- *Second PIE at INP: completed*
  Oxidation test for irradiated samples

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)



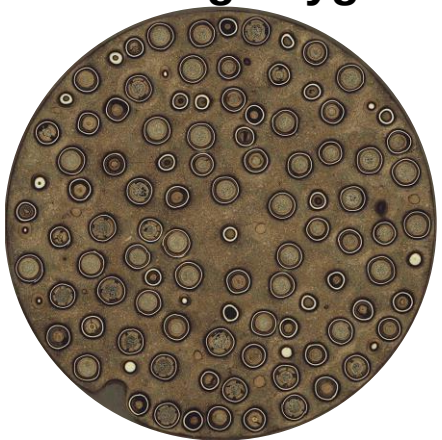
X-rays of simulated coating defects

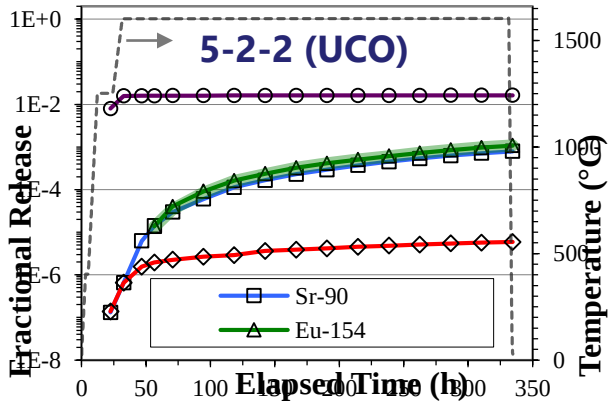


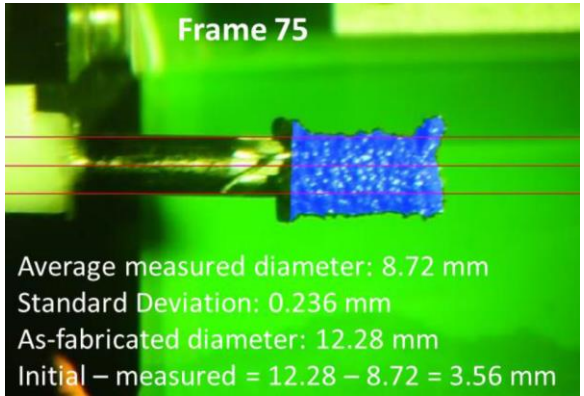
FFC Progress: USA

- **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**

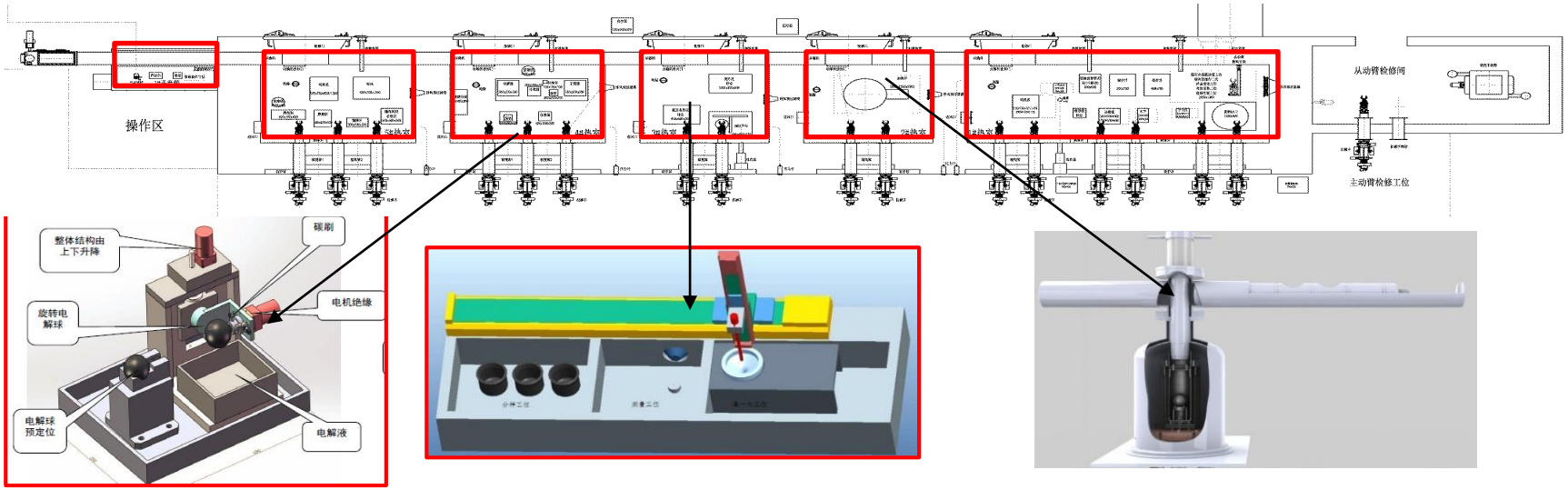






FFC Progress: China

- **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.**



Deconsolidation **IMGA** **KÜFA**

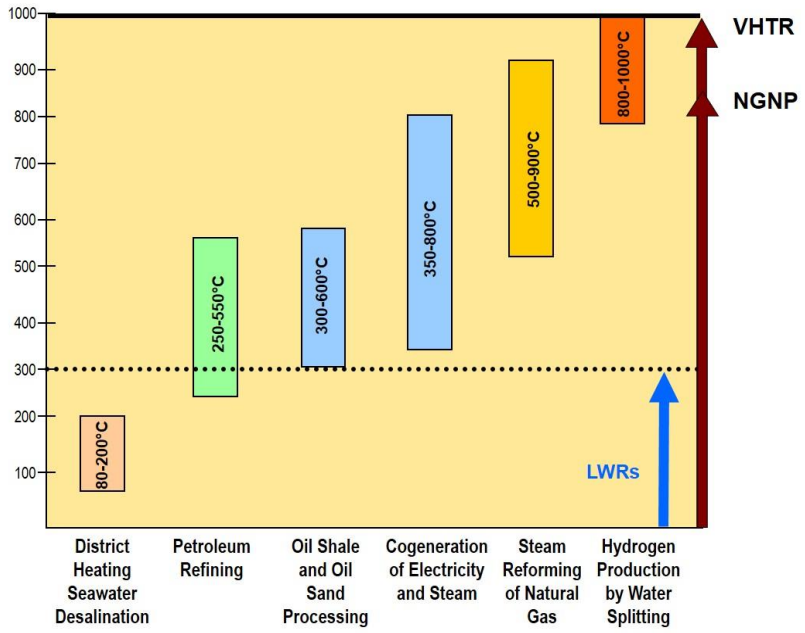
2.3 H_2 Production

Objectives:

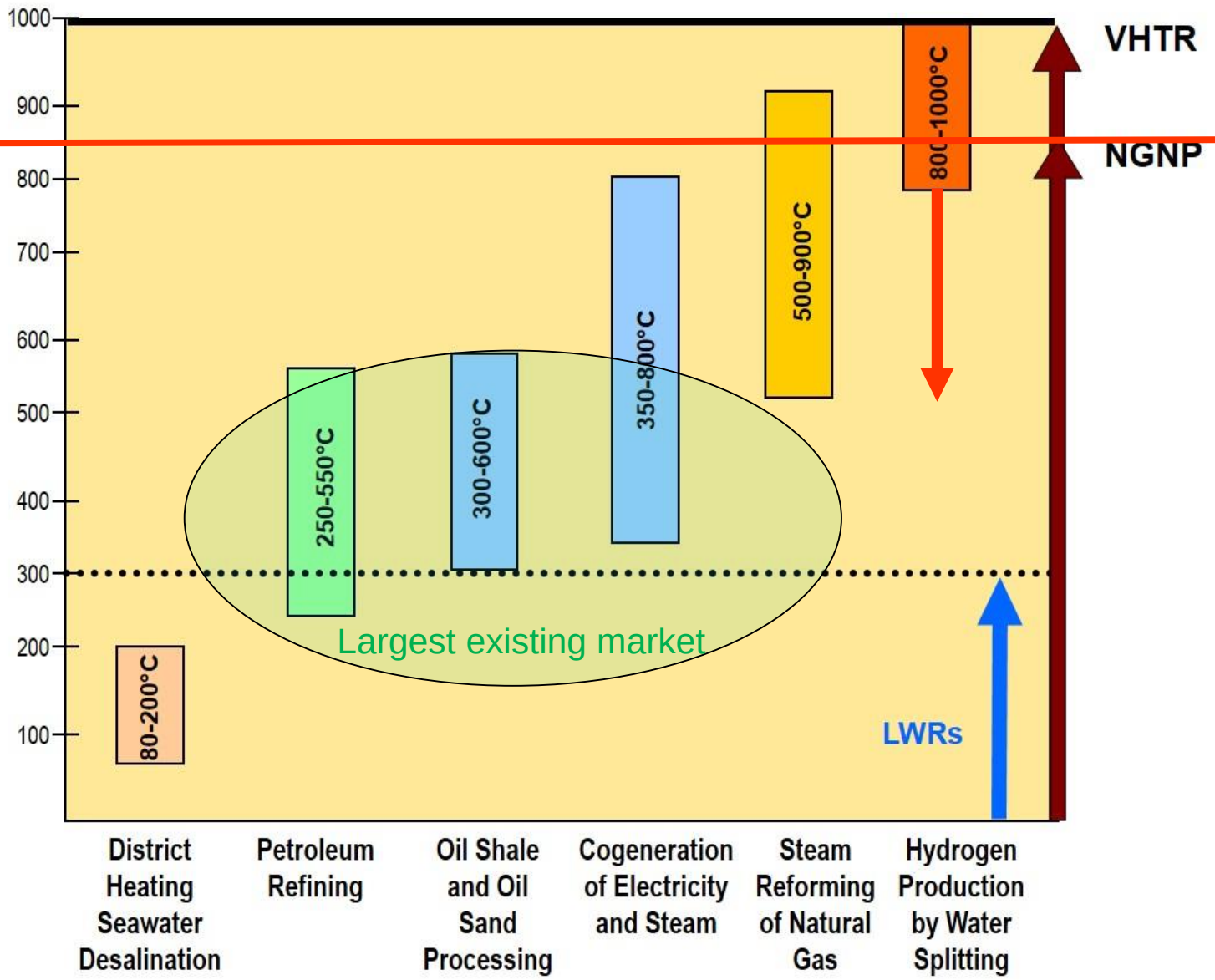
Was original driver for VHTR development.

After initial work by several signatories,

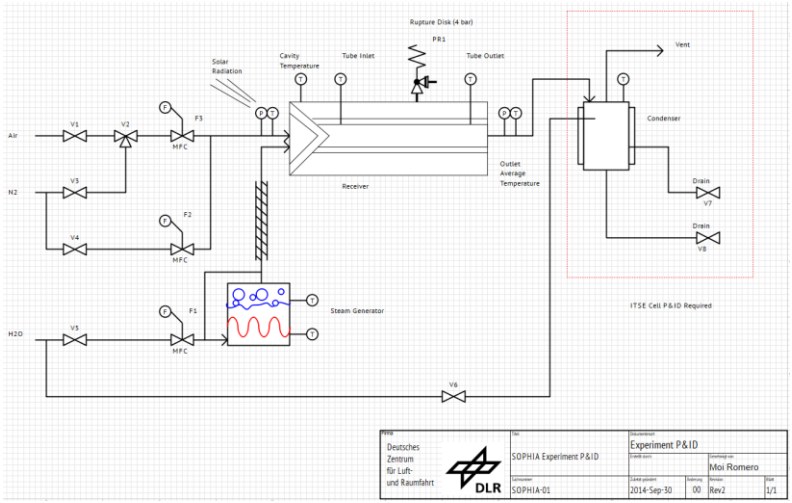
SI and HTSE identified as most promising.



- 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


1000
900
800
700
600
500
400
300
200
100
VHTR
NGNP
800-1000°C
500-900°C
350-800°C
300-600°C
250-550°C
80-200°C
Largest existing market
LWRs
District Heating Seawater Desalination
Petroleum Refining
Oil Shale and Oil Sand Processing
Cogeneration of Electricity and Steam
Steam Reforming of Natural Gas
Hydrogen Production by Water Splitting

2.3 H_2 Production



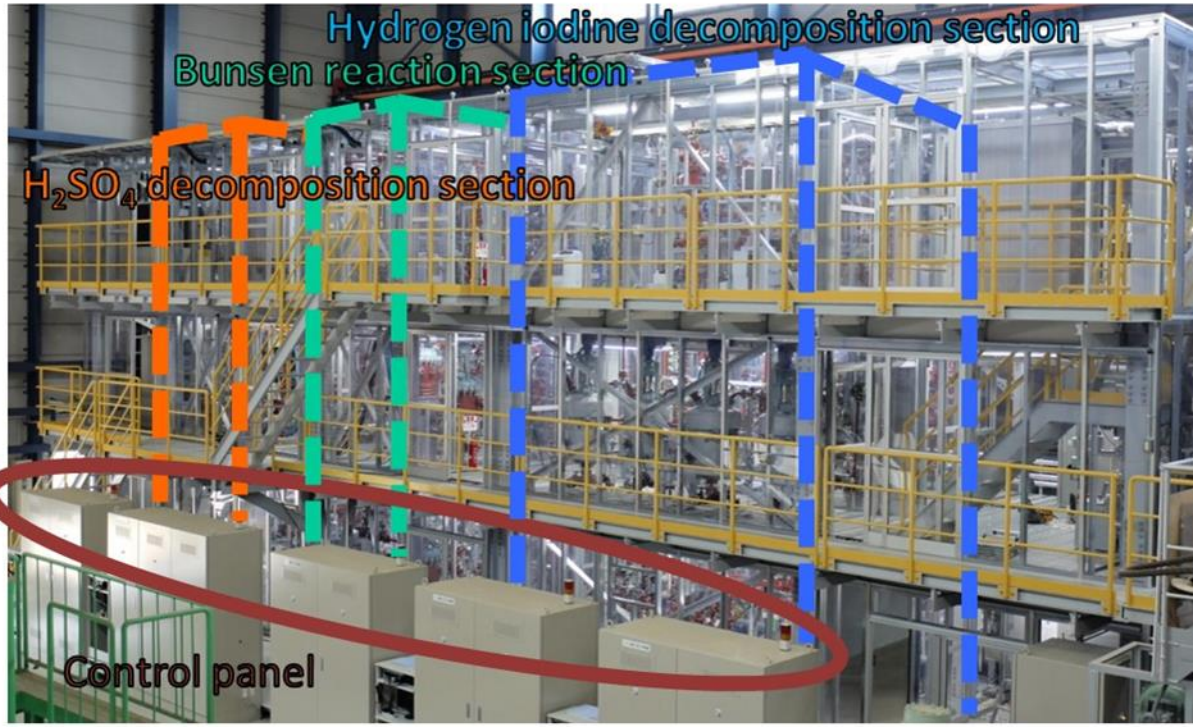
- **Signatories:** CDN, EU, FR, US, KR, JA + CN
- Most recent PMB meeting Cologne, Germany, 17-19 October 2017
- **Processes:**
  - Sulfur/Iodine cycle: KR, JA, CN
  - High-Temperature Steam Electrolysis: FR, US, EU, CN, CDN
  - Hybrid copper-chloride cycle: CDN
  - Hybrid sulfur cycle: ?
- **Output:**
  - Use of HTTR as heat source will enhance credibility of nuclear H_2 production;
  - Good: Contributions from non-nuclear projects
  - Project successfully re-invigorated, more collaboration

2.3 H_2 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 H_2 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 H_2 for Hybrid Energy Systems;
- **China (observer):** Safety of SI process, development of prototype acid decomposers for H_2SO_4 and HI;

2.3 H_2 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.



Hydrogen production test facility at JAEA Oarai

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)


HTR-PM He circulator test facility

➔ 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

KAERI Hybrid RCCS Test Facility

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
6. Energy System Integration (Advanced Energy Use and Storage Methods, Hybrid Energy Systems)

➔ 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

Vendor	Product
CNNC	HTR-PM, 250 MWth / HTR-PM600, 600 MWe, pebble bed, electricity
AREVA Inc.	SC-HTGR, 625 MWth, block, cogen, http://us.areva.com/EN/home-3225/areva-inc-areva-htgr.html
(NIA/NC2I/KNHA)	NHSS, 350 MWth (200 – 625 MWth), block, cogen, www.ngnpalliance.org
X-Energy	Xe-100, 200 MWth, pebble bed, https://www.x-energy.com/
HTMR	HTMR-100, 100 MWth, pebble bed, http://www.thorium100.com/HTMR-100%20Reactor.php
Starcore Nuclear	36 MWth + 20 MWe, cogen, static pebble bed (2013, http://starcorepower.com), now block (http://starcorenuclear.ca)
JAEA	GTHTR-300, 600 MWth, block, electricity, cogen, H_2, http://httr.jaea.go.jp/eng/
U Battery cons.	U Battery, 10 MWth, block, cogen, https://www.u-battery.com/what-is-u-battery

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

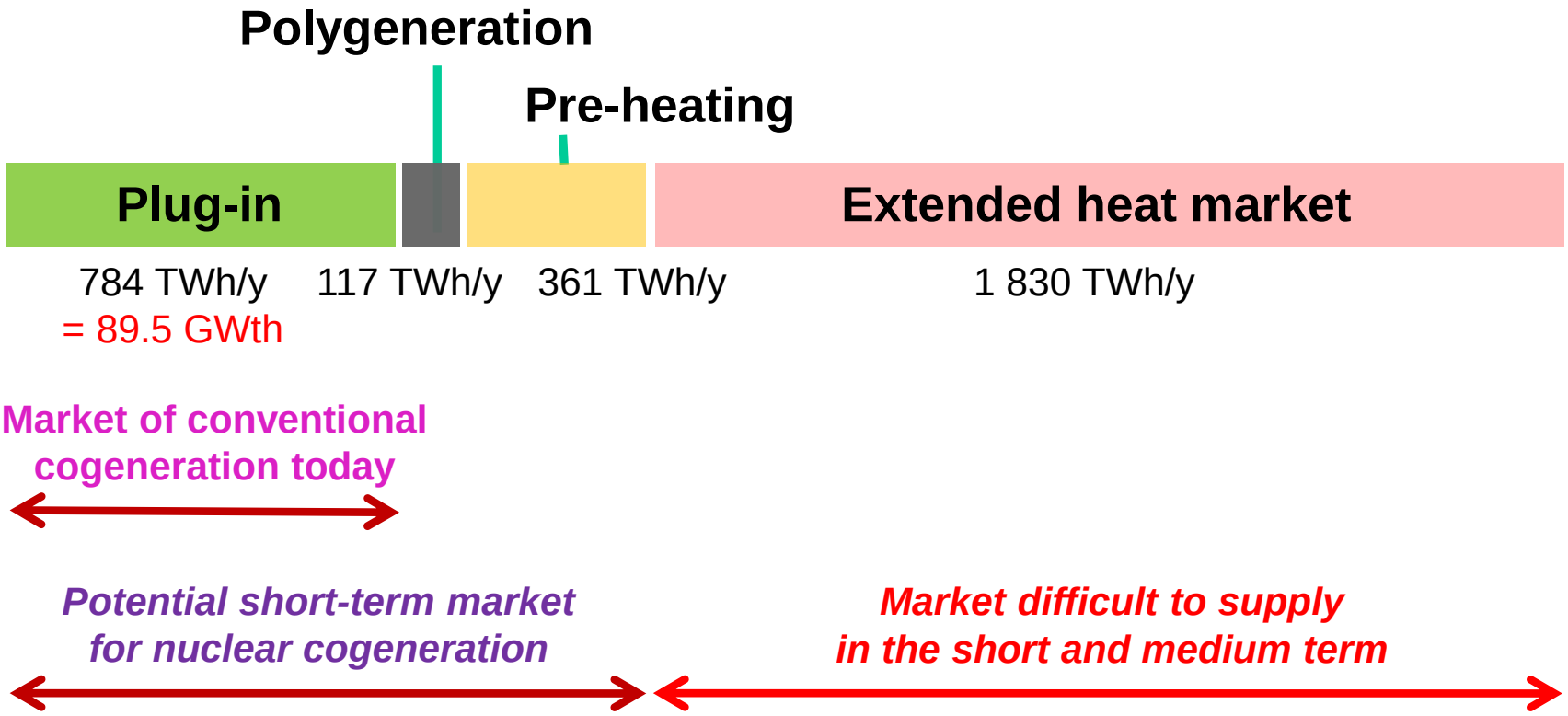
6. Market Studies and Economics

Region	Plug-in market	Total market	GDP 2011 (approx.)
Europe	~ 800 TWh/y *(EUROPAIRS)*	~ 3,000 TWh/y *(EUROPAIRS)*	17,000 bn€ / 25% of world
USA	~ 1,100 TWh/y *(MPR Associates)*	~ 3,600 TWh/y *(MPR Associates)*	15,000 bn€ / 22% of world
Japan		*1,000 – 1,400 TWh/y (est.)*	5,900 bn€ / 8% of world
China		*1,200 – 1,700 TWh/y (est.)*	7,000 bn€ / 10% of world
India		*300 – 500 TWh/y (est.)*	2,000 bn€ / 3% of world
Russia		*300 – 500 TWh/y (est.)*	2,000 bn€ / 3% of world
World total	~~*3,000 – 5,000 TWh/y*~~ ***~ 370 – 630 GWth***	***11,000 – 16,000 TWh/y***	**69,000 bn€**

Not a niche market but room for several hundred reactors!

Source: Bredimas

6. Market Size in EU28



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, H_2)
  - 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