Recent Advances of the Very High Temperature Reactor System

Michael A. Fütterer (EU)

on behalf of the
GIF VHTR System Steering Committee
michael.fuetterer@ec.europa.eu

Outline

1. System overview
2. Status of Cooperation, Projects and Highlights
    - Materials
    - Fuel and Fuel Cycle
    - Hydrogen Production
    - Computational Methods, Validation & Benchmarks
3. Interaction with other GIF groups
4. Future collaborative projects
5. Related International Activities
6. Wrap-up

1. System Overview

- **7 Signatories:** CH, EU, FR, JP, KR, US, CN
  + CDN in H_2 Production project
  + Australia in Materials project
- **Validity** of SA: 30 November 2016; signature process for extension underway (delayed due to late FA extension)
- Most recent SSC Meeting: 11-12 November 2016 in Las Vegas

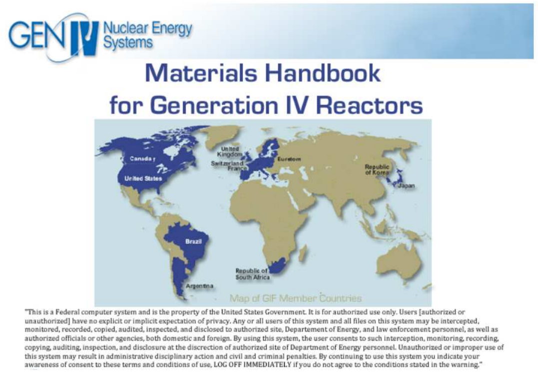
Active projects:

1. **Materials**
2. **Fuel and Fuel Cycle**
3. **Hydrogen Production**
4. **Computational Methods, Validation & Benchmarking (provisional)**

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.

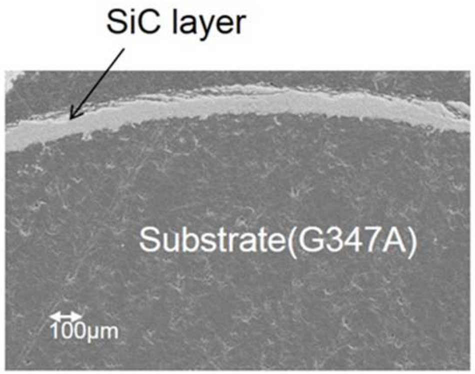
Materials handbook: developed and used to store and manage VHTR data, facilitate international R&D co-ordination and support modelling to predict damage and lifetime.

2.1 Materials

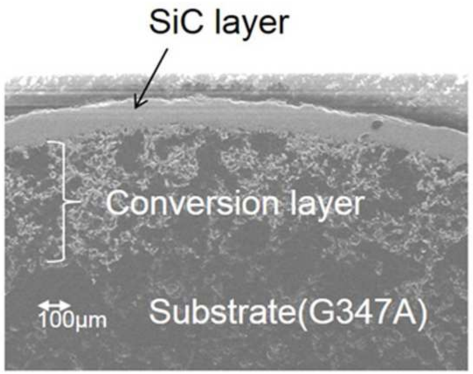
- **Validity:**
  - new PA -2018 (including CN and AUS)
- **Signatories:** CH, EU, FR, JA, KR, US
  - CDN, - RSA, + CN
  + Australia: high T materials, welding, irradiations, corrosion
  new PA will include Australian contribution;
- **Structure:** 3 WG on Graphite, Metals, Ceramics
- **Output:** extremely productive, material test data, design codes and standards
- **Crosscutting workshops:** (<u>with PMBs from other systems</u>)
  - on metals: organized by EU at CV Rez (April 2016)
  - arrangement for informal cross-system information exchange desired
  - session on next GIF Symposium requested

2.1 Materials

- Focus on near- and medium-term project needs: graphite and high-T alloys
- Graphite characterization and testing before and after irradiation
- Oxidation protection (SiC, boron, and B_4C coatings): JA, KR, US



Cross section of the specimen manufactured by Standard method



Cross section of the specimen manufactured by Improved method

- Development of codes and standards for nuclear graphite
- Development and submission of ASME Code Case for Alloy 617 (< 950°C, < 100,000 h)
- Irradiation, irradiation creep, creep crack growth of 9Cr-1Mo (and ODS steels) including in weldments for RPV
- Creep in 2.25Cr-1Mo steel for steam generators

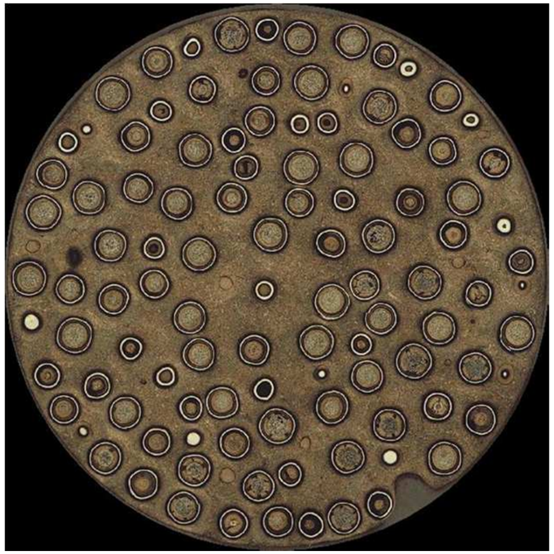
2.2 Fuel and Fuel Cycle

Objectives:

- Test (and understand!) performance of UO_2/UCO TRISO coated particles with SiC/PyC coating and advanced coatings for enhanced burnup, minimum fission product release and maximum safety (resistance to core heat-up accidents >1600°C).
  - Fuel characterization
  - Chemical/ thermo-mechanical properties in normal and accidental conditions
  - Irradiation testing
  - Post-irradiation examination
  - Safety testing
  - Fission product release evaluation
- Spent-fuel treatment and disposal
- Used-graphite management
- Deep-burn of plutonium and minor actinides (MA) in support of a closed cycle

2.2 Fuel and Fuel Cycle

- **Validity:** - Phase 1 PA: 2006 – 2011, - Phase 2 PA: 2012 – 2017
  Phase 3 PA under preparation
- **Signatories:** US, KR, EU, JA
  - CDN, - CH, FR (observer), + CN (Jan. 2014)
- **Structure:** Phase 2 Workplan 2012-17:
  1. Irradiation and PIE
  2. Fuel Attributes and Material Properties
  3. Safety testing
  4. Enhanced and Advanced Fuel Fabrication
  5. Waste management

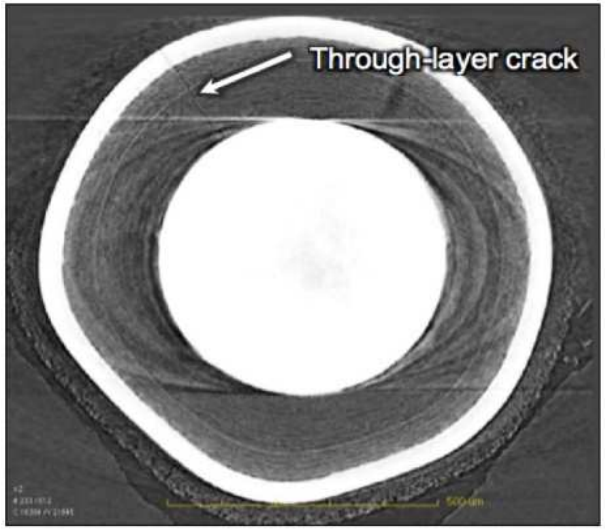


Cross section of an AGR-2 UCO fuel compact irradiated (11.0% FIMA, time-peak T 1305°C)

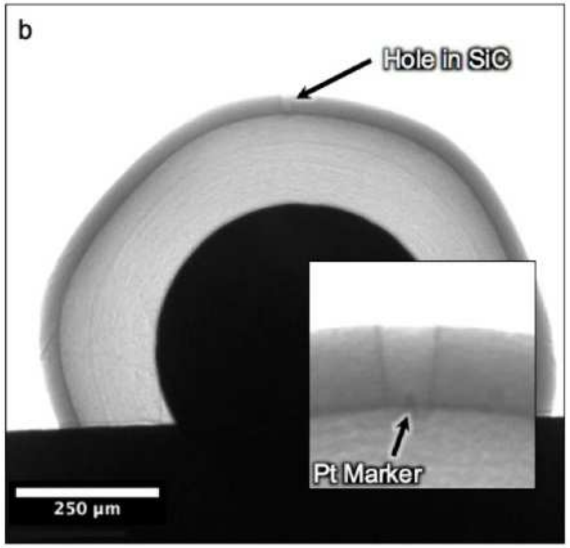
- **Productive collaboration:**
  - Several workshops on SiC coating properties
  - Irradiation testing, now with emphasis on PIE and safety testing
  - Burn-leach round robin (sharing particles to validate key QC measurements)
  - Workshops on design of heating furnaces, fuel deconsolidation and IMGA
  - Code validation of irradiation tests and accident heating tests

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



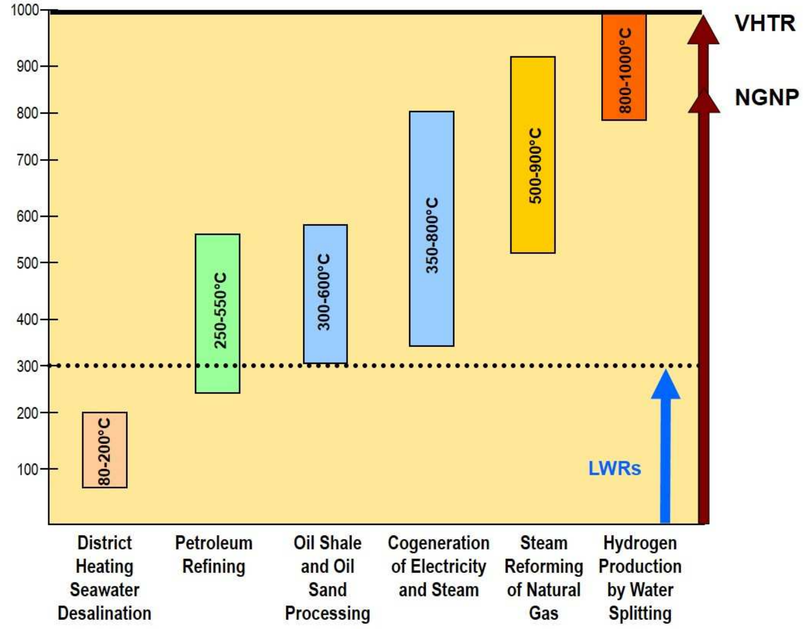
2.3 Hydrogen Production

Objectives:

Was original driver for VHTR development.

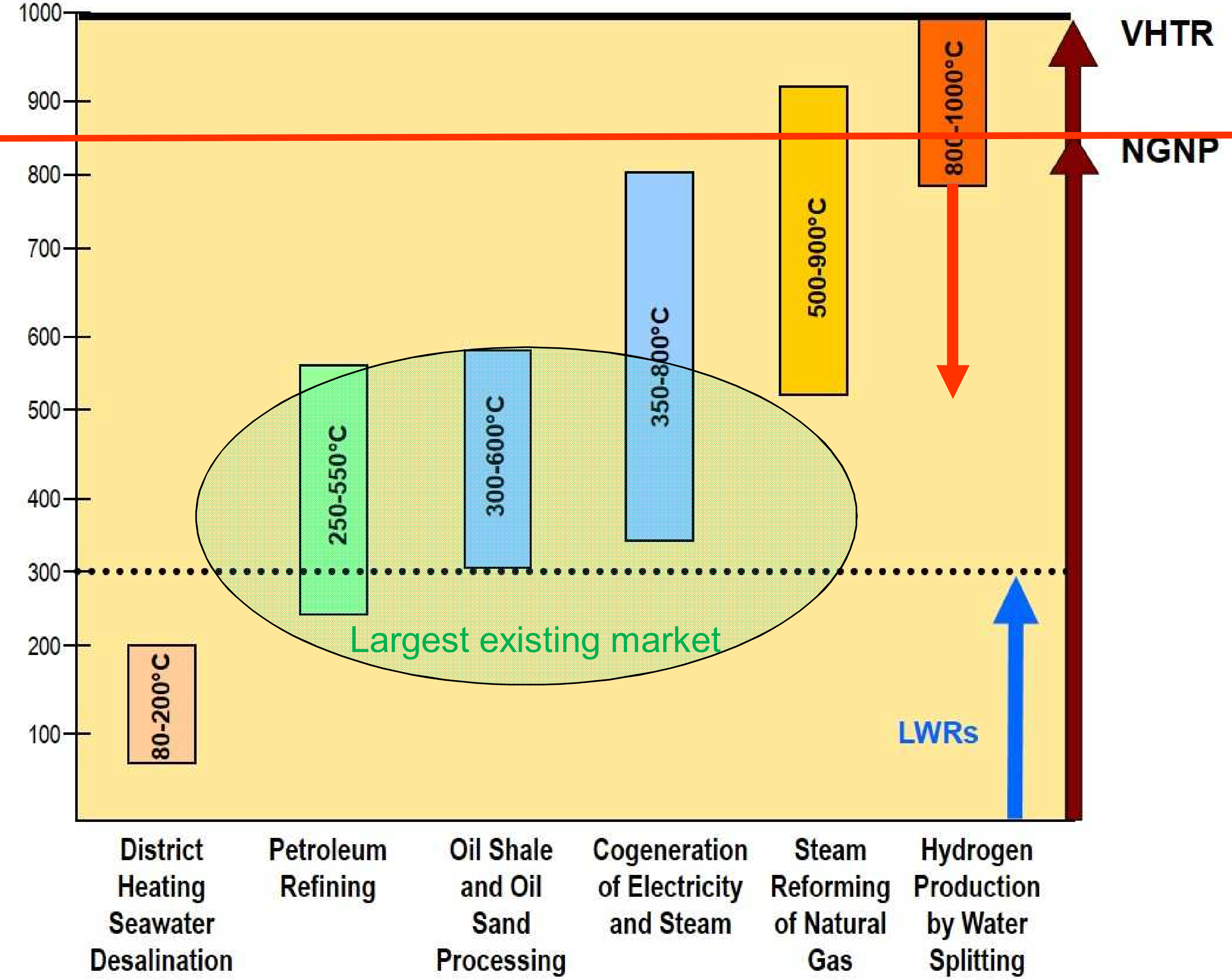
After initial work by several signatories,

SI and HTSE identified as most promising.

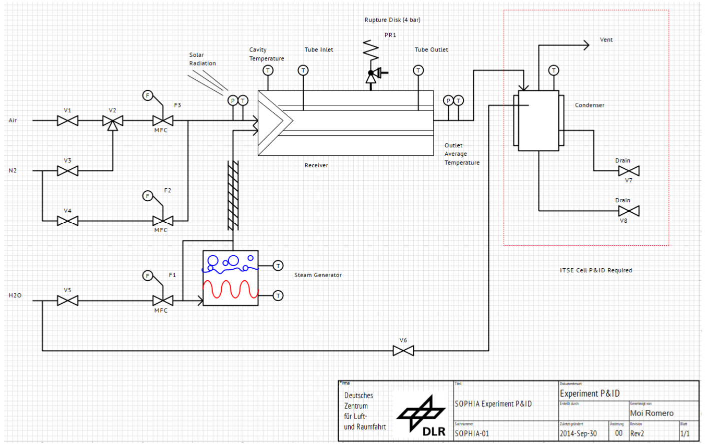


- Feasibility, optimization, efficiency and economics at small and large scale
- Performance and optimization in test loops, from lab scale through pilot and demo scale
- Component development (e.g. advanced process heat exchangers)
- Coupling technology with the nuclear reactor incl. risk analysis of 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 Hydrogen Production



2.3 Hydrogen Production

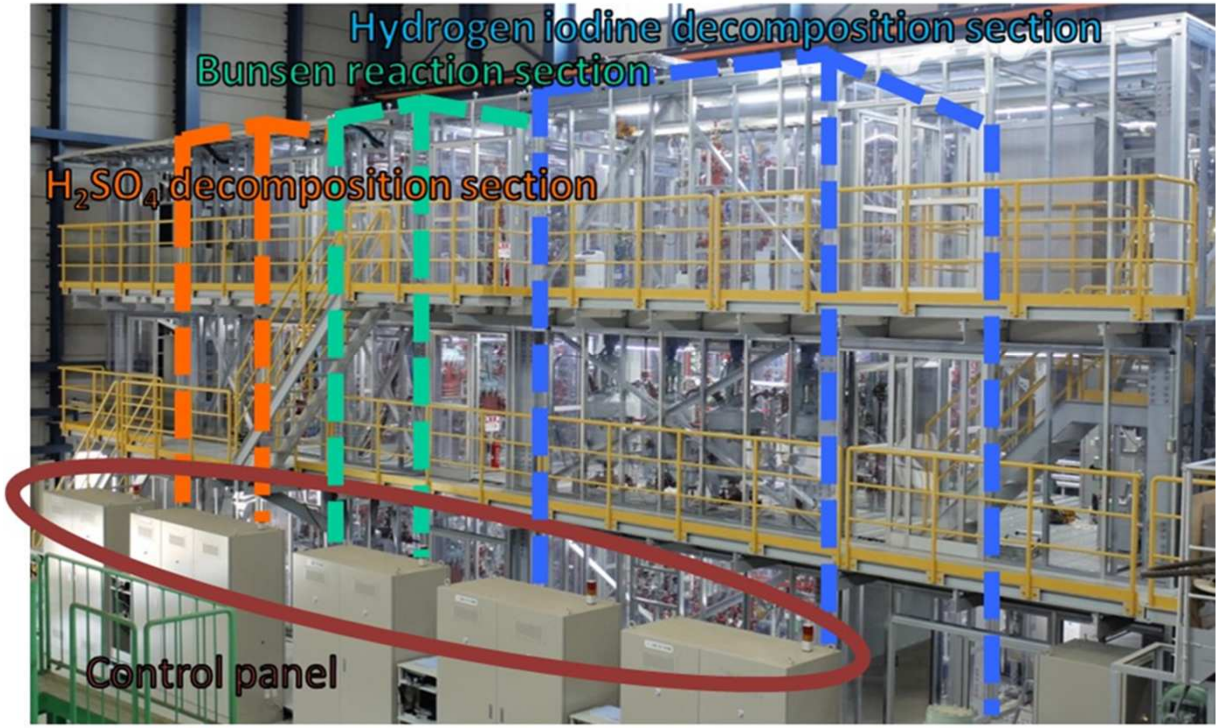


- **Validity:** current PA - 2018
- **Signatories:** CDN, EU, FR, US, KR, JA + CN
- **Processes:**
  - ➢ Sulfur/Iodine cycle: KR, JA, CN
  - ➢ High-Temperature Steam Electrolysis: FR, US, EU, CN, CDN
  - ➢ Hybrid copper-chloride cycle: CDN
  - ➢ Hybrid sulfur cycle: ?

- **Output:**
  - – Use of HTTR as heat source will enhance credibility of nuclear H_2 production;
  - – Good: Contributions mainly from non-nuclear projects
  - – Project successfully re-invigorated, more collaboration instead of work in parallel

2.3 Hydrogen 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 & Benchmarks (provisional)

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


HTR-PM He circulator test facility

- 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)

➔ facilitate the elimination of unnecessary design conservatisms and improve construction cost estimates

2.4 Computational Methods, Validation & Benchmarking (provisional)

- **Validity:** PA to be signed after FA signed by all signatories (spring 2017) detailed task contribution sheets were prepared
- 2 constructive PMB meetings in 2016
- **Signatories:** CN, EU, JA, KR, US
- **Structure:** 5 Work Packages
  1. Phenomena identification and ranking table (PIRT) methodology (lead EU)
  2. Computational fluid dynamics (CFD) (lead CN)
  3. Reactor core physics and nuclear data (lead US)
  4. Chemistry and transport (lead CN)
  5. Reactor and plant dynamics (lead CN)

- **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. Interaction with other GIF groups

- **GIF RSWG:**
  White Paper and Self Assessment under preparation in iteration with RSWG;
- **GIF PRPP WG:** interaction dormant; no clear benefits for PMBs;
- **GIF EMWG:** interaction to be reinforced, in particular to reduce cost uncertainties and to identify avenues for cost reduction R&D (e.g. on graphite cost)
- **GIF SIAP:** first contact established, focus on industrial aspects of demonstration and deployment;
- **GIF Sustainability Task Force:**
  Extension of task force to be discussed at next EG;
  GIF has bias towards fuel resource sustainability;
- **GIF Education and Training Task Force:**
  - VHTR SSC participates in LinkedIn group:
  - Prepared a webinar (25 January 2017)
  https://www.gen-4.org/gif/jcms/c_87678/webinar-series-5-very-high-temperature-reactors-dr-carl-sink

4. Future collaborative R&D topics

- **Targeted towards demonstration and long-term performance.**
- **Some topics suitable for collaboration within GIF, others more for IAEA or OECD/NEA or bilateral collaboration frameworks.**
- **Headlines:**
  1. Materials (advanced), Components and Supply Chain
  2. Design, System Integration and Cost Reduction
  3. Safety Demonstration and Licensing
  4. Fuel, (advanced) Fuel Cycle, and Waste Minimization
  5. Coupling to Cogeneration Applications and Hybrid Energy Systems
  6. Advanced Energy Use and Storage Methods

➔ Ample opportunities for further fruitful cooperation on HTGR, VHTR and process heat applications

5. Related international activities

GEMINI/PRIME

- Joint effort of NC2I & NGNP IA for demonstration
- MoU signed June 2014
- Workshops in Paris, Washington, Piketon, Brussels, Las Vegas
- Participation of Korea and Japan currently being explored
- Related EU project approved on 16 February 2017 (GEMINI+)
- Modular design to meet common needs:
  - similar components
  - 300 or 600 MWth (1 or 2 loops)

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;

HTR Conferences

HTR 2016: 6-10 November 2016, Las Vegas (200 technical papers plus invited talks)
HTR 2018: October 2018 in Warsaw, Poland

6. 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
- 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)
  - GEMINI (EU+US), BATAN (Indonesia), StarCore Nuclear (Canada), X-Energy (US), HTMR (UK), STL (RSA)
  - HTTR (Japan) waiting for regulator OK
  - HTR-10 (China) is running
  - HTR-PM (China) start-up at end-2017
- Cooperation with IAEA and OECD/NEA