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High Temperature Gas-cooled Reactors in a European Electricity Supply Environment; Main Outcomes of a Project in PSI

Nuclear Science and Technology Symposium - SYP2019 Helsinki, Finland, 30-31 October 2019
Introduction: HTGRs

- High temperature gas-cooled reactor (HTGR)
- Common features: Gas cooling (He), high (700-900 °C) outlet gas temperature
- Several built and operated between 60s and 90s.

Picture: IAEA-TECDOC-1645
Introduction: HTGRs

- High temperature gas-cooled reactor (HTGR)
- Common features: Gas cooling (He), high (700-900 °C) outlet gas temperature
- Several built and operated between 60s and 90s.
Introduction: HTR-PM

- HTR-PM is a 250 MWth twin unit, modular pebble bed reactor, currently being build in Shandong province, China
- Jan. 2019: first steam generator hoisted, grid connection 2020 (ref. CNNC)
- Most of the work in this project focused on the HTR-PM

Pictures: http://www.world-nuclear-news.org/
Past: PROTEUS at PSI

- Zero power reactor (max. 1 kW), February 1968 - April 2011
- Cylindrical central cavity (Ø1.2 m) driven critical by a surrounding graphite region equipped with fuel pins containing UO$_2$ with an enrichment of 5%
- Part of an International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) on the Validation of Safety Related Physics Calculations for Low Enriched HTGRs.
Past: pebble movement and wear study at PSI

- Investigation on graphite dust creation due to wear on pebbles caused by pebbles sliding against each other and reactor walls.
- Pebble movement simulations were performed with full scale reactor with 440000 pebbles
  - Different parameters investigated: pebble velocity and pebble bed packing density, effect of the friction coefficient (0.2 - 0.8).

• In years 2015-2019, Paul Scherrer Institut (PSI) conducted a project: Feasibility and plausibility of innovative reactor concepts in an European electricity supply environment”.
  – Main focus on modern pebble bed high temperature reactor, tie in with earlier studies on pebble bed reactors carried out at PSI.
  – Main purpose to build-up the specific HTGR know-how in Switzerland / provide in-depth information to decision makers / identify research needs for the future.
• Specific topics from different research areas.
  – Focus on the student projects (MSc & semester/summer work)
  – Main focus on HTR-PM design
Specific research & knowledge base

- Economic assessment
- Accident analysis
- Fuel cycle studies
- Waste volume reduction
- Summary and future research

Know-how update, preservation & acquisition

Regular meetings and seminars with the Tsinghua university Beijing – INET, on various topics on the HTGRs

Specific interest:
- Inherent safety features
- Engineered safety systems
**Economic assessment of HTGRs**

- **Estimating the costs of Small Modular Reactors**
- **Top-down methodology** - based on reference cost data from similar existing technologies (or the ones being built) adjusted (e.g. by scaling) to analyzed subject design
- Including 4 iPWRs and HTR-600

### Cost Estimation

\[
Cost_{new} = Cost_{ref} \times \left( \frac{Power_{new}}{Power_{ref}} \right)^a
\]

<table>
<thead>
<tr>
<th>Account</th>
<th>Scaling factors</th>
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<tbody>
<tr>
<td>Small changes in power output</td>
<td>Large changes in power output</td>
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<tr>
<td>Structures and Improvements</td>
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<tr>
<td>Reactor Plant Equipment</td>
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<tr>
<td>Turbine Plant Equipment</td>
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<td>Electric Plant Equipment</td>
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<tr>
<td>Miscellaneous Plant Equipment</td>
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<tr>
<td>Heat Rejection System</td>
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<tr>
<td>Construction Service</td>
<td>0.45</td>
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<tr>
<td>Field Office Eng. &amp; Service</td>
<td>0.4</td>
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<tr>
<td>Owner’s cost</td>
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<table>
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<tr>
<th>4 most developed iPWRs</th>
<th>HTR-600</th>
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<tbody>
<tr>
<td>Technology group</td>
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<tr>
<td>ACP100</td>
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<td>SMART</td>
<td>HTR</td>
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<td>Country</td>
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<td>100 MWe</td>
<td>30 MWe</td>
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<td>50 MWe</td>
<td>100 MWe</td>
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<td>100 MWe</td>
<td>600 MWe</td>
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<tr>
<td>Reference plant</td>
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<tr>
<td>ACP1000 at Yangjiang</td>
<td>Hualong One</td>
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<td>planned to be built</td>
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<td>Summer and</td>
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<td>Vogtle</td>
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<td>APR1400 at</td>
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<td>Shin Haul</td>
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<td>HTR-PM demo plant</td>
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Economic assessment of HTGRs

- Estimating the costs of Small Modular Reactors
  - HTGR - Cost breakdown data for the HTR-PM -> estimated costs for a scale up to a 600 MWe design -> cost reductions for shared equipment in a 2x600 MWe plant -> learning curve cost reductions (10 %)
  - Comparison to a reference: Chinese Generation II+ CPR1000 design, using the costs of the Fuqing 1-3 reactors.

### 4 most developed iPWRs

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### Cost Breakdown

- Nuclear island
- Conventional island
- Balance of plant
- Pre-construction work
- Project management
- Engineering services
- Production preparation
- Other costs
Accident study in HTR-PM using MELCOR code

- MELCOR 2.2 code used to simulations of Pressurized and De-pressurized loss of forced flow accidents (PLOFC/DLOFC) in the HTR-PM
- The input from open literature on HTR-PM and earlier HTGR work MELCOR

Figures: Kalilainen et al. HTR2018
MELCOR 2.2 code used to simulations of Pressurized and De-pressurized loss of forced flow accidents (PLOFC/DLOFC) in the HTR-PM
• The input from open literature on HTR-PM and earlier HTGR work MELCOR
• Comparison to analysis by Zheng et al., Ann Nucl Energy 36 (2009)

**Figures:** Kalilainen et al. HTR2018

For more information, please refer to: Kalilainen et al. Paper HTR 2018-618, proceedings of HTR2018, Warsaw, Poland.
Fuel cycle studies for pebble bed HTGRs

- **Statistical burnup distribution of moving pebbles in HTR-PM reactor**
- Loose coupling of the exact pebble movement with the parametrized cross sections (XS) generated with Monte Carlo code Serpent for the full-core in HTR-PM
- MATLAB burnup script developed to simulate the multi-pass fuel loading scheme of the HTR-PM

(MPB script, MSc thesis of F. Vitullo, EPFL Lausanne, 2017)
Fuel cycle studies for pebble bed HTGRs

- Statistical burnup distribution of moving pebbles in HTR-PM reactor
- Loose coupling of the exact pebble movement with the parametrized cross sections (XS) generated with Monte Carlo code for the full-core in HTR-PM
- Burnup history of 3000 pebbles evaluated

For more information please refer to: Vitullo et al., 2019. Statistical Burnup Distribution of Moving Pebbles in HTR-PM reactor. Accepted for publishing in Journal of Nuclear Engineering and Radiation Science. https://doi.org/10.1115/1.4044910.
Fuel cycle studies for pebble bed HTGRs

- Closed equilibrium fuel cycle study of HTGR
  - HTGRs cannot be operated in a closed fuel cycle with purely fertile feed

- Initial / transition fuel cycle study for HTR-PM:
  - Analysis of Th pebbles as initial burnable poison
  - Utilization of natural resources not improved in any of the simulation cases.

Excess reactivity in Th-U. For more information, please refer to: Krepel et al., Ann. Nucl. Energy 128, 2019

For more information, please refer to: Sisl et al. Proceedings of HTR 2018, Warsaw, Poland, October 8-10, 2018
Waste volume reduction by pebble fragmentation for HTGRs

- Cost assessment on the direct disposal of the pebble fuel
- Possibilities for cost reductions through waste management measures

Spent fuel pebbles

- Direct disposal of unprocessed pebbles
  - ~123 CHF/MWh

- Direct disposal of coated particles (HLW) and graphite (LLW) separately
  - ~8.02 CHF/MWh

- Direct disposal of coated particles (HLW) and graphite recycling
  - ~6.82 Cent/MWh

Not included:
- Interim storage costs
- Transport casks
- Conditioning costs
- Bonus due to SiC barriers
- Bonus due to lower decay heat
- Bonus due to lower activity

Know how update, preservation & acquisition
Waste volume reduction by pebble fragmentation for HTGRs

- **Cost assessment on the direct disposal of the pebble fuel**
  - Possibilities for cost reductions through waste management measures
- **Feasibility study of a combined transport and treatment canister for HV pulse fragmentation experiments with irradiated pebbles**


Vivek Maradia, 2018: Design for a canister with shielding
Summary and future research needs

- Several studies on modern modular pebble bed reactor were performed, including:
  - Economic assessment of the HTR-600
  - Loss of forced cooling accidents in HTR-PM
  - Fuel cycle option for HTGRs: use of Th-U fuel and burnup distribution in HTR-PM
  - Waste volume reduction study
- Several potential research topics were identified at the end of the project. These include:
  - Advanced simulation of accident scenarios in modular pebble bed reactors in addition to LOFC accidents, including:
    - Hypothetical extreme accidents and emergency measures
    - Release of fission products during the accident and normal operating conditions
  - Advanced fuel cycle studies: effect of pebble clustering
  - Advanced economic study: fuel cycle cost, capital cost development
Wir schaffen Wissen – heute für morgen

Kiitos!