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PSI

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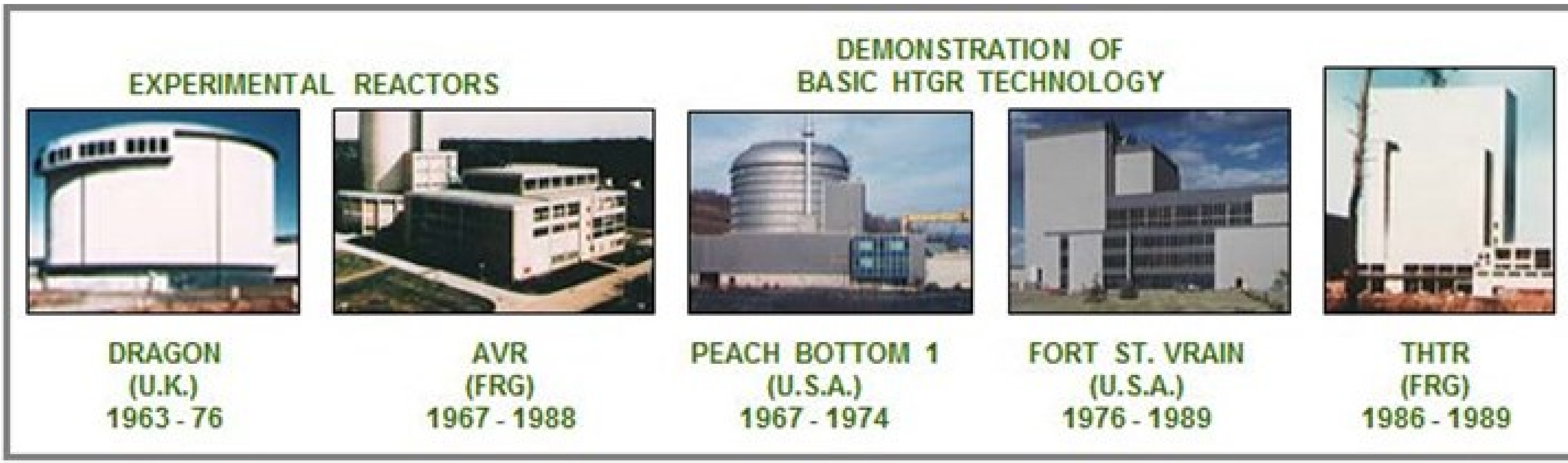
High Temperature Gas-cooled Reactors in a European Electricity Supply Environment; Main Outcomes of a Project in PSI

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

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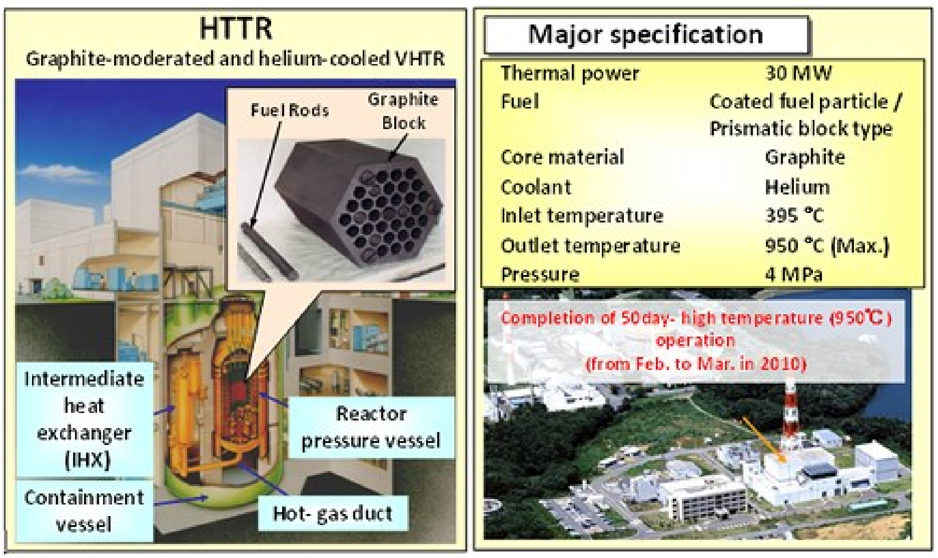
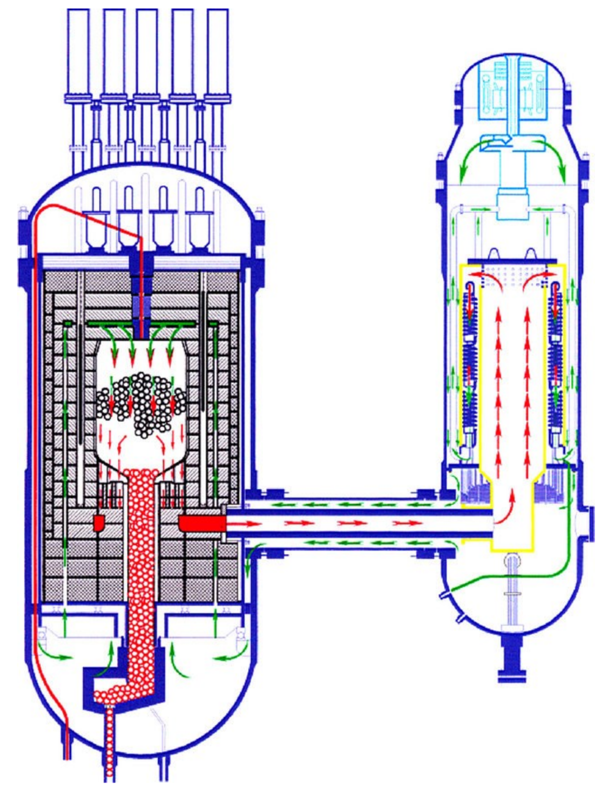


Picure: www.jaea.go.jp



Chinese 10 MW high-temperature gas-cooled test reactor (HTR-10)

Picture: Zhang et al., Nucl. Eng. Des. 239, 2009

Introduction: HTR-PM

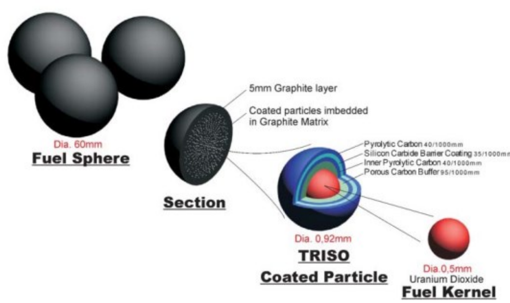
– HTR-PM is a 250 MWth twin unit, modular pebble bed reactor, currently being build in Shandong province, China

– Jan. 2019: first steam generator hoisted, grid connection 2020 (ref. CNNC)

– Most of the work in this project focused on the HTR-PM

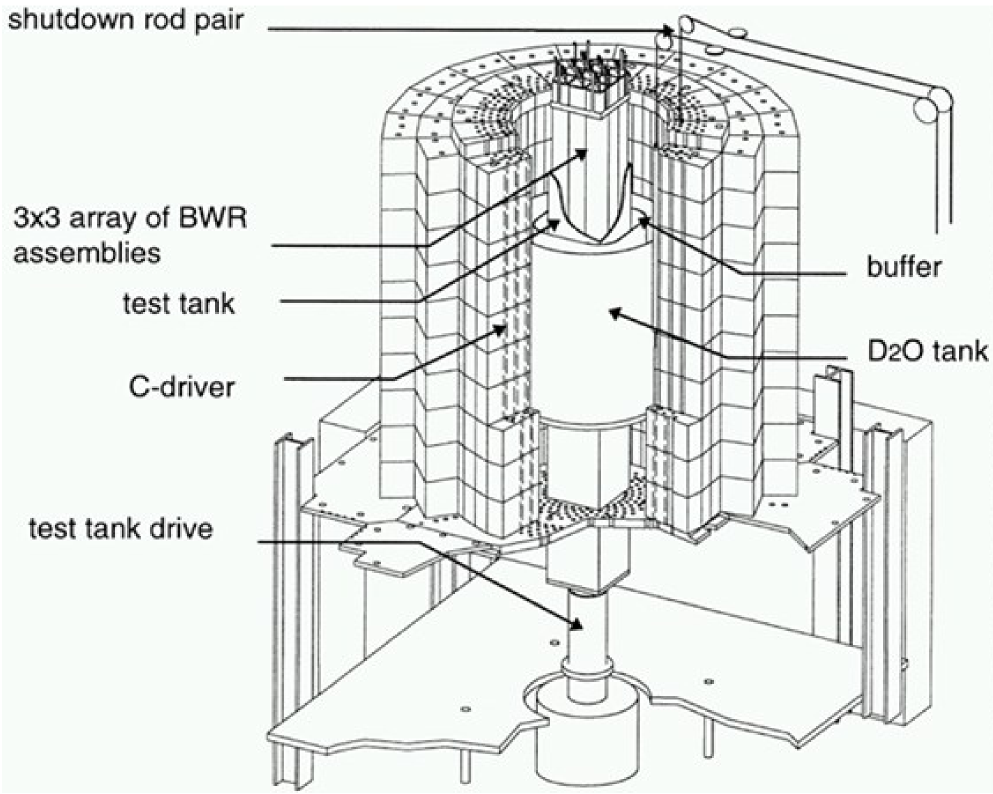
Picture: IAEA I3-TM-50156

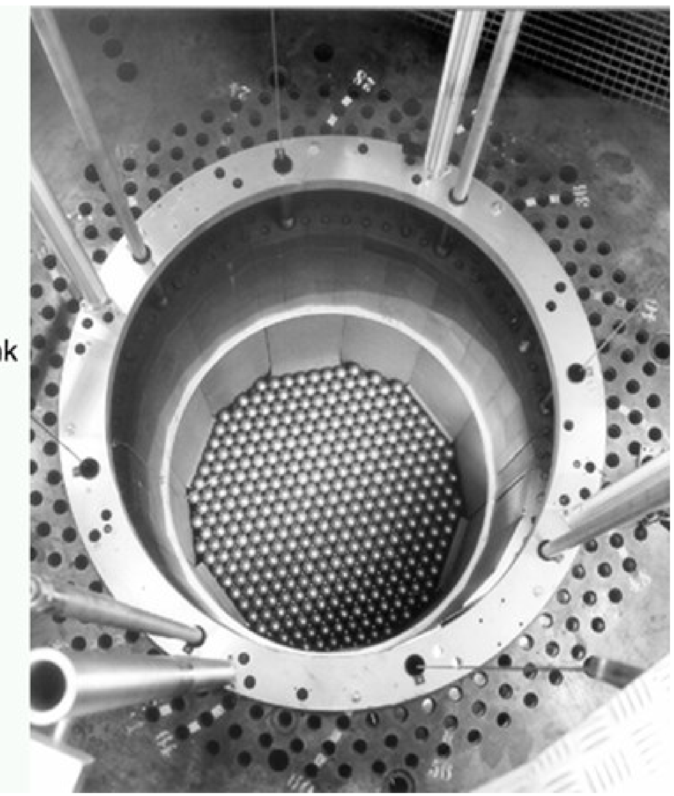
Pictures: http://www.world-nuclear-news.org/



Picture: https://nuclearstreet.com/

Past: PROTEUS at PSI

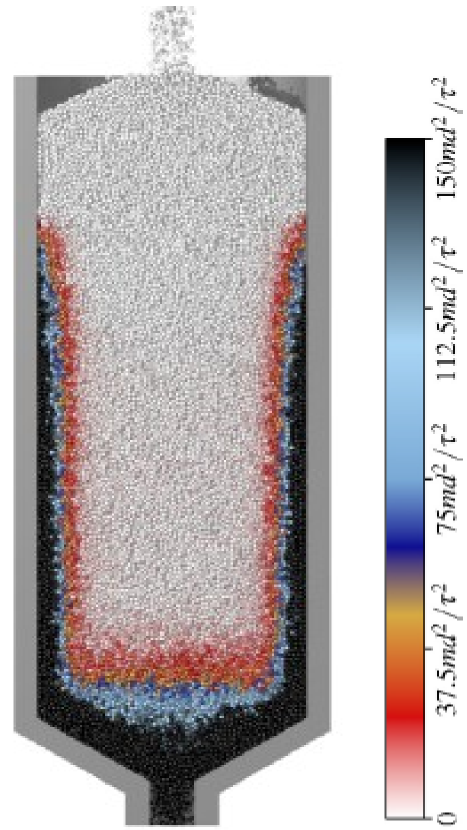




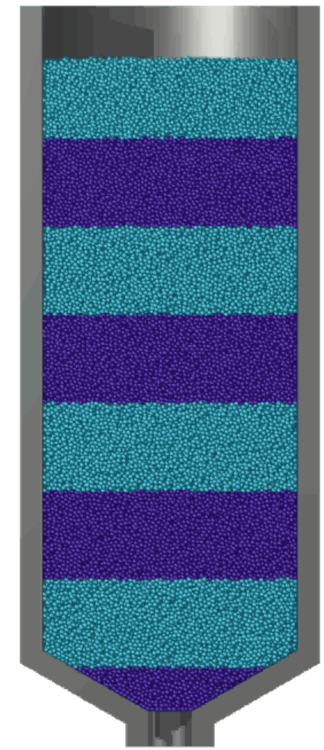
- Zero power reactor (max. 1 kW), February 1968 - April 2011
- Cylindrical central cavity (∅1.2 m) driven critical by a surrounding graphite region equipped with fuel pins containing UO_2 with an enrichment of 5 %
- Part of an International Atomic Energy Agency (IAEA) Coordinated Research Project (CRP) 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).



Snapshot when approx. 20 % of pebbles drained. Amount of wear particle experiences in units of work with μ=0.35.



Full size reactor drainage simulation.

Rycroft et al., 2013. *Granular flow in pebble-bed nuclear reactors: Scaling, dust generation and stress*. Nucl. Eng. Des. 265, 69-84.

Introduction: Recent PSI project on HTGR

- 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

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

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

- **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

4 most developed iPWRs — HTR-600

	ACP100	CAREM	NuScale	SMART	HTR-600
Technology group	iPWR	iPWR	iPWR	iPWR	HTR
Country	China	Argentina	U.S.A	South Korea	China
Electrical Power	100 MWe	30 MWe	50 MWe	100 MWe	600 MWe
Reference plant	ACPR1000 at Yangjang	Hualong One planned to be built	AP1000 at Summer and Vogtle	APR1400 at Shin Kori and Shin Haul	HTR-PM demo plant

INET
清华大学 Tsinghua University

Account	Scaling factors	
	Small changes in power output	Large changes in power output
Structures and Improvements	0.5	0.59
Reactor Plant Equipment	0.6	0.8
Turbine Plant Equipment	0.8	0.83
Electric Plant Equipment	0.4	0.39
Miscellaneous Plant Equipment	0.3	0.59
Heat Rejection System	0.8	1.06
Construction Service	0.45	0.69
Field Office Eng. & Service	0.4	0.69
Owner's cost	0.5	0.64

$$Cost_{new} = Cost_{ref} * \left(\frac{Power_{new}}{Power_{ref}}\right)^{a}$$

From MSc thesis of P. Dobrzynski, 2017

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Economic assessment of HTGRs

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

- **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 | **HTR-600**

	ACP100	CAREM	NuScale	SMART	HTR-600
Technology group	iPWR	iPWR	iPWR	iPWR	HTR
Country	China	Argentina	U.S.A	South Korea	China
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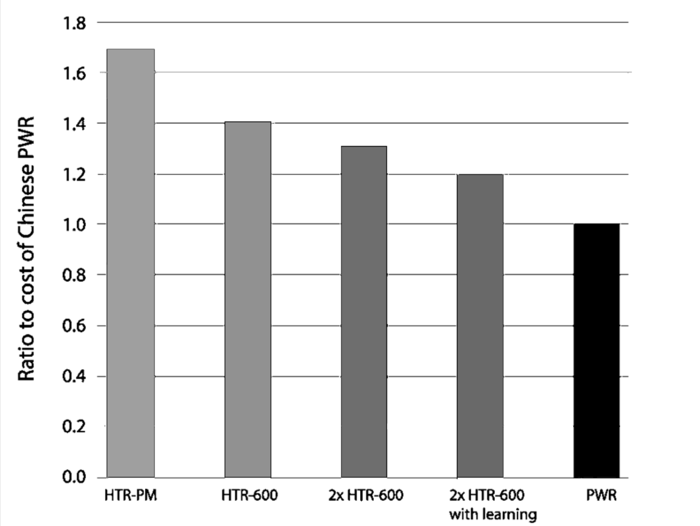
INET

Tsinghua University



Costs considered in the study:

- Nuclear island
- Conventional island
- Balance of plant
- Pre-construction work
- Project management
- Engineering services
- Production preparation
- Other costs

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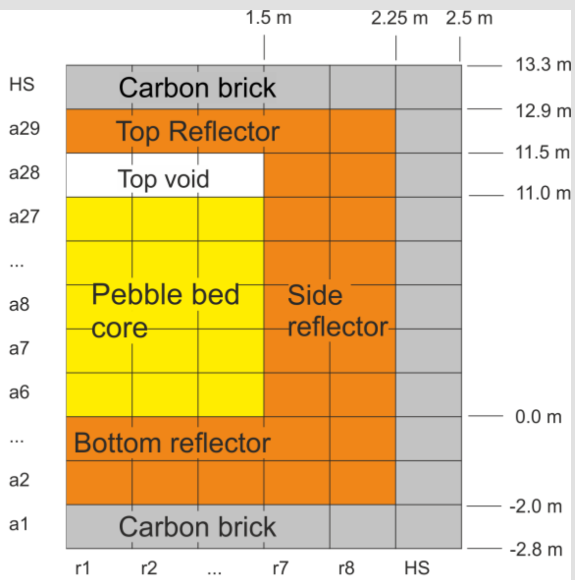
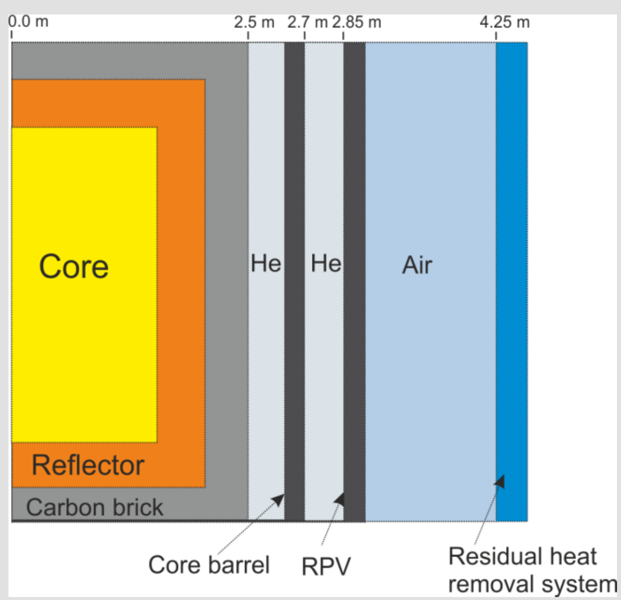
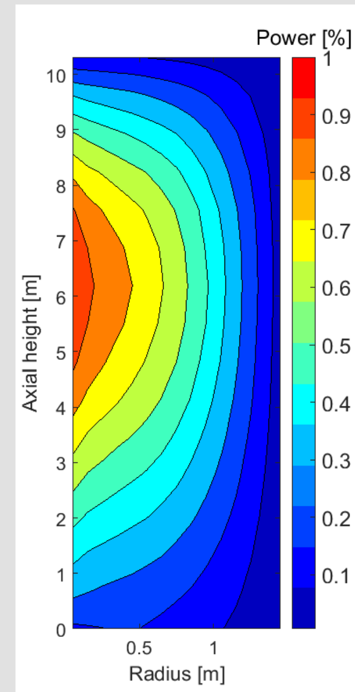
Accident study in HTR-PM using MELCOR code

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

- **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*

Accident study in HTR-PM using MELCOR code

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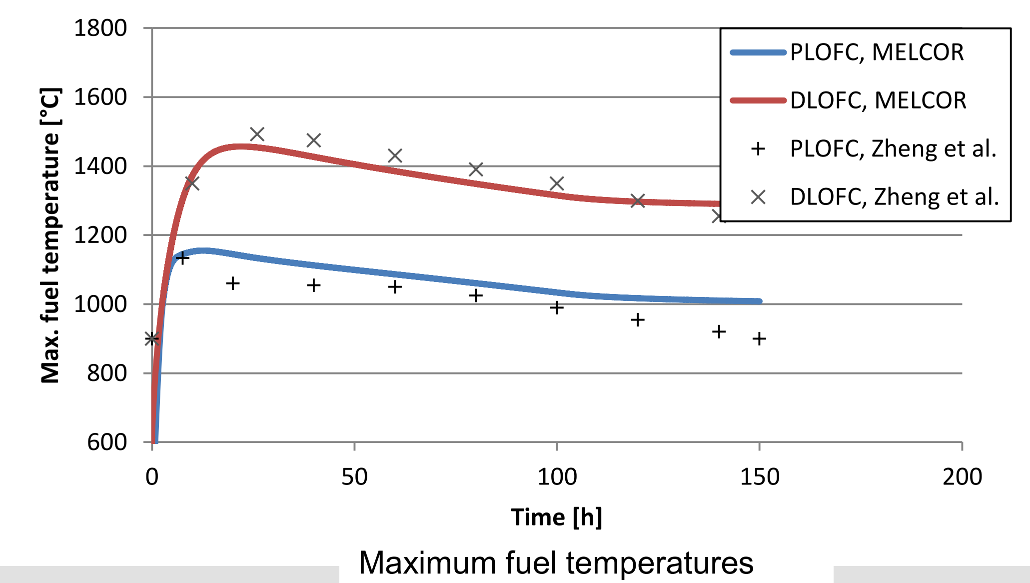
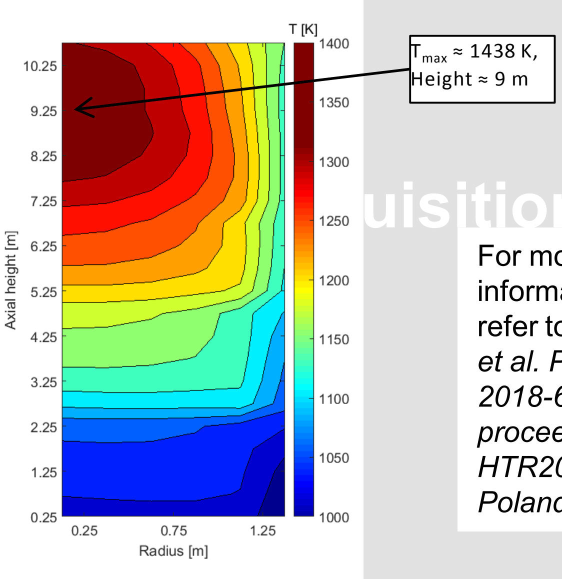
- The input from open literature on HTR-PM and earlier HTGR work MELCOR
- Comparison to analysis by Zheng et al., Ann Nucl Energy 36 (2009)



Maximum fuel temperatures



Fuel temperature during the PLOFC accident

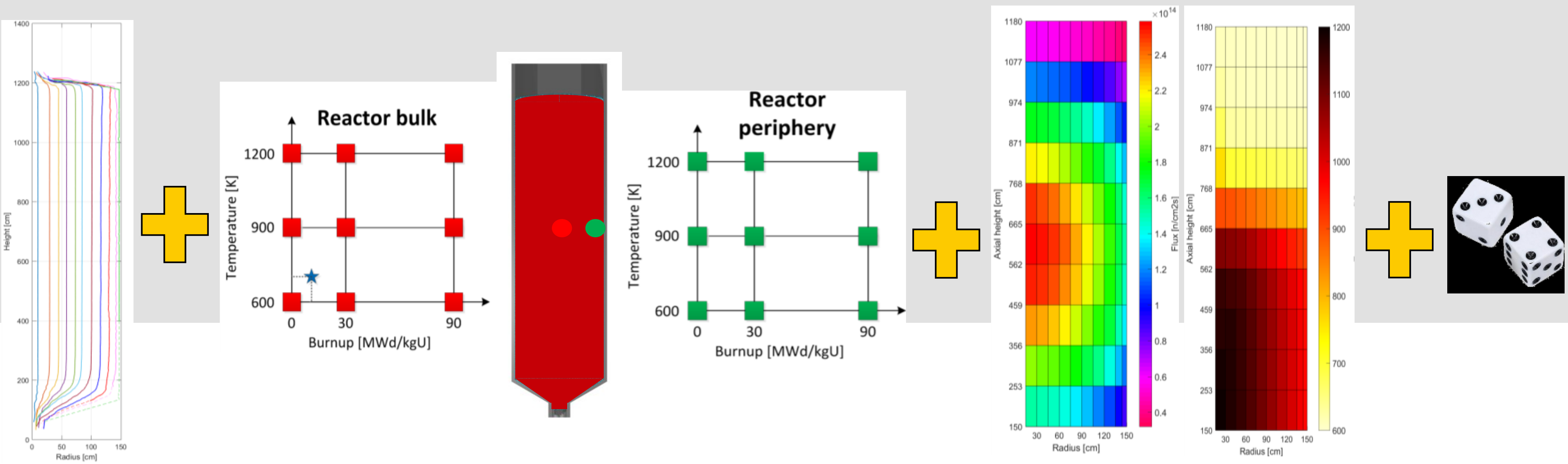
For more information, please refer to: *Kalilainen et al. Paper HTR 2018-618, proceedings of HTR2018, Warsaw, Poland.*

Figures: *Kalilainen et al. HTR2018*

Fuel cycle studies for pebble bed HTGRs

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

- **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

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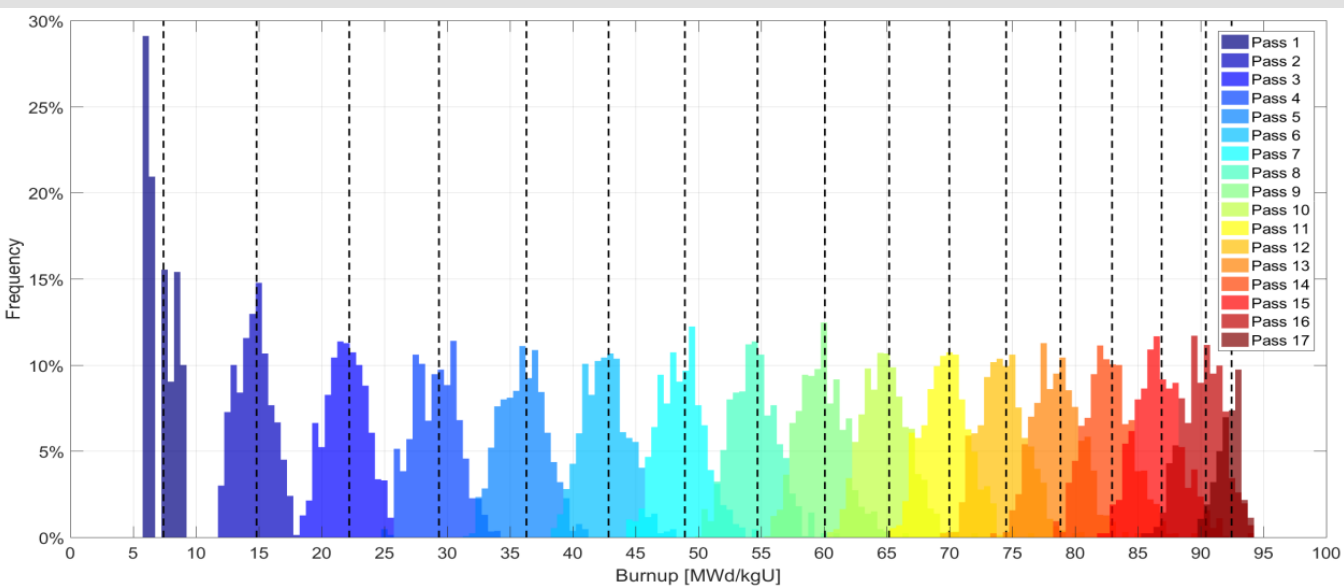
- **Statistical burnup distribution of moving pebbles in HTR-PM reactor**
- Loose coupling of the exact pebble movement with the parametrized cross sections (XS) generated with Monte Carlo code for the full-core in HTR-PM
- Burnup history of 3000 pebbles evaluated



Statistical burnup distribution for each pass through the HTR-PM reactor with 16 passes fuel cycle, (Vitullo et al., 2019).

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

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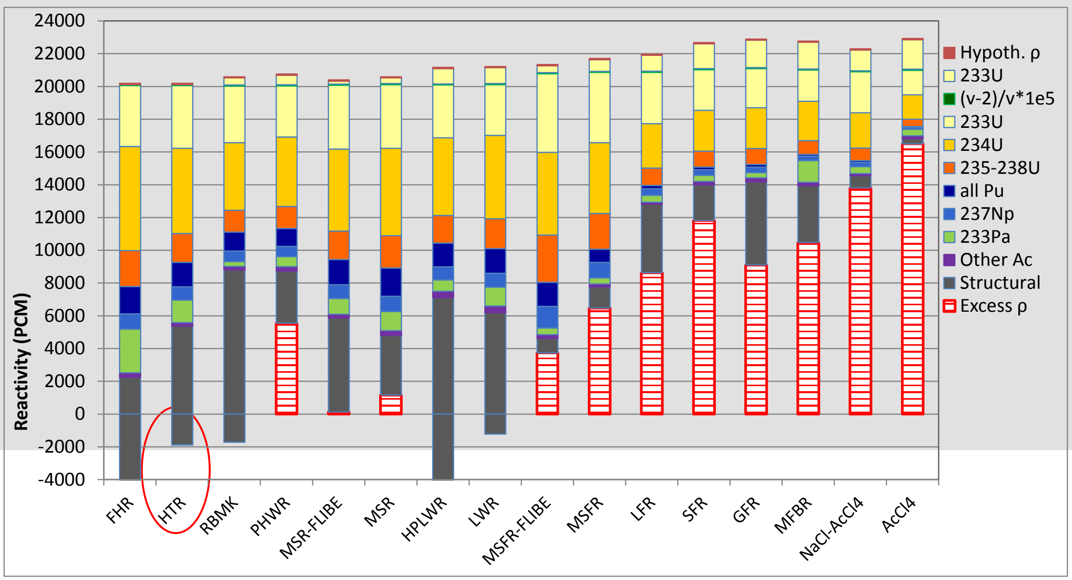
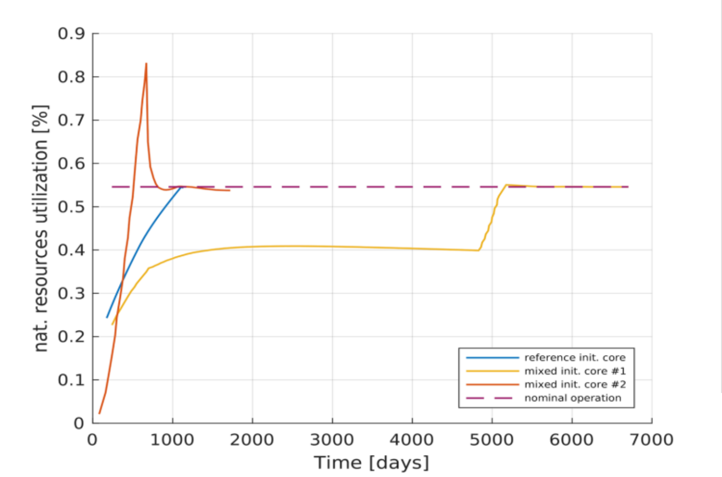
- **Closed equilibrium fuel cycle study of HTGR**
  - HTGRs cannot be operated in a closed fuel cycle with purely fertile feed

- **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*

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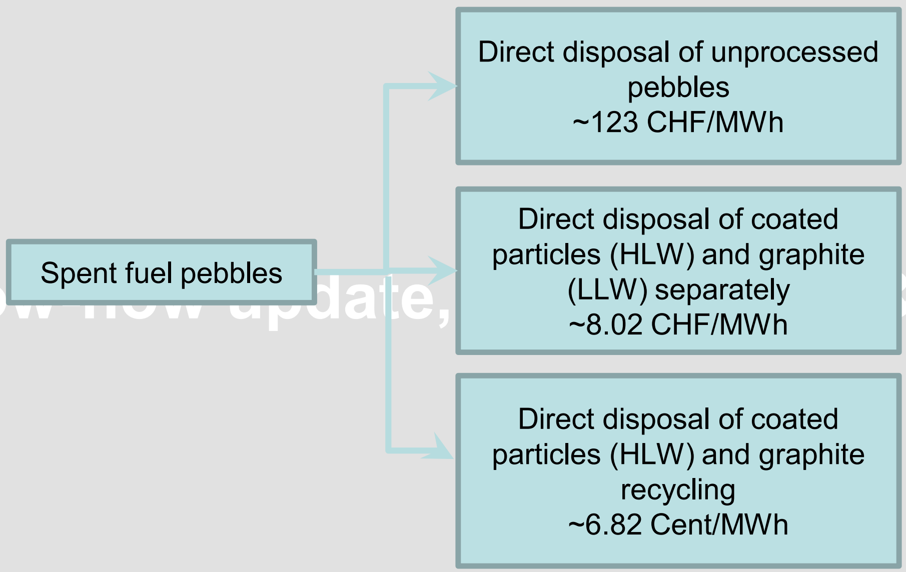
Waste volume reduction by pebble fragmentation for HTGRs

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



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

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**

Fig. 6. Crushed fuel pebble after 3 seconds (15 pulses)

3 seconds of exposure (15 pulses)

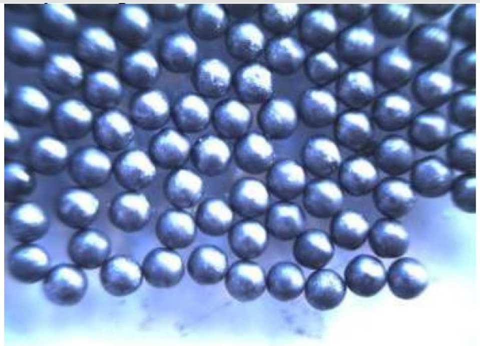
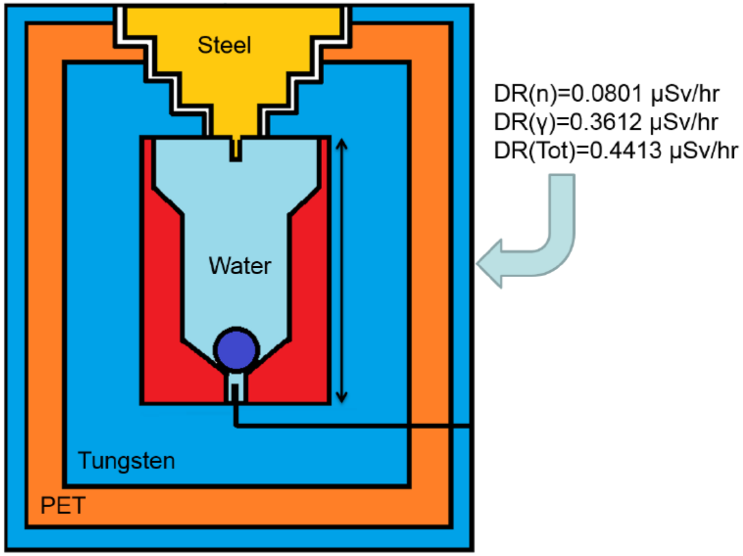


Fig. 7. Liberated coated particles (∅1 mm)

1 minute of exposure (300 pulses)

Pictures above: M. A. Fütterer et al.: A High Voltage Head-End Process for Waste Minimization and Reprocessing of Coated Particle Fuel for High Temperature Reactors. Proceedings of ICAPP ’10.



Vivek Maradia, 2018: Design for a canister with shielding

Summary and future research needs

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

- 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

Kiitos!