HTGR Technology Course for the Nuclear Regulatory Commission

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Module 6d

Pebble Bed HTGR Refueling Design

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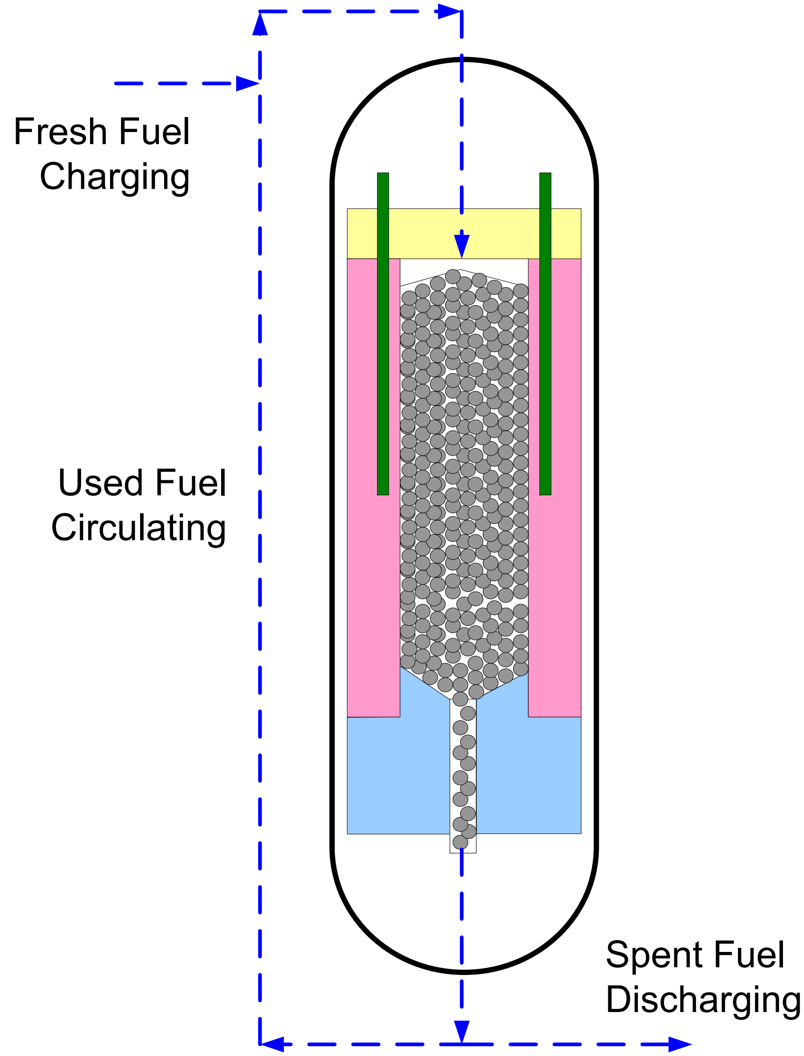
Outline

- Principal functions and features of Pebble Bed Fuel Handling System (FHS)
- Fuel Handling System operation
- Fuel Handling System experience and lessons learned

Principal Functions of Pebble Bed Fuel Handling System

- Charge fresh fuel from storage
- Circulate used fuel
- Discharge spent fuel to storage
- Allow core to be unloaded and reloaded
- Limit planned shutdowns to be compatible with most process heat users



On-line Refueling System Features

- Flexibility to introduce fuel for a different fuel cycle on-line
- Core design uncertainty is reduced by measuring each fuel sphere for burnup instead of calculating
- Excess reactivity can be adjusted on-line by changing the refueling parameters
- No reload analyses are required and approach to criticality is only required on initial core load or when the core is reloaded from the used fuel tank
- Automated and closed fuel handling system allows for accounting of all fuel at any time
- The safeguards approach for the pebble-bed uses integrated inventory control rather than the traditional item control. This approach has been successfully used by the IAEA on AVR and THTR

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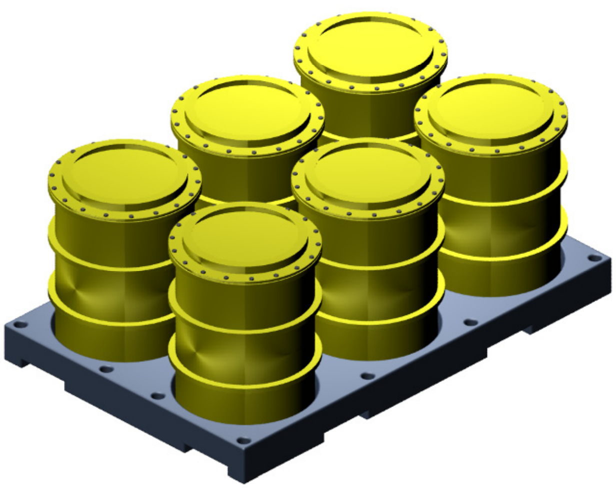
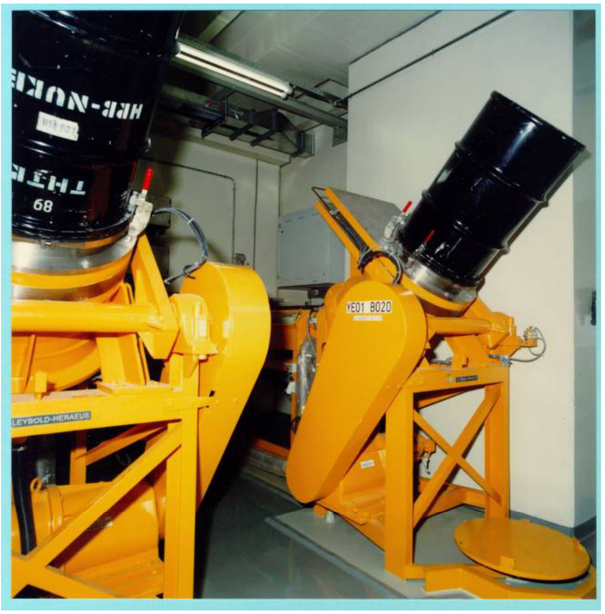
Fuel Charging Operation

- Fresh fuel is normally stored in drums on site
- Fresh fuel is charged from the drums in to the circulating circuit to replace spent fuel
- Sufficient drums are stored for ~180 days of operation without resupply





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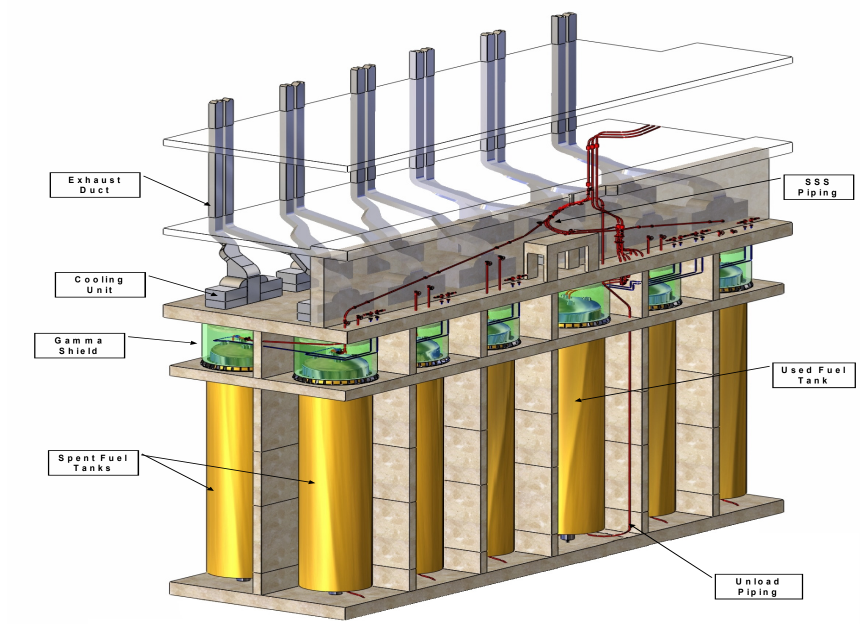
Fuel Circulation Operation

- **Extract spheres from the bottom of the core by means of gravity, this allows spheres to move down through the core**
- **Separate out broken/damaged spheres**
- **Measure each sphere for burnup**
- **When a sphere has reached its burnup limit, discharge as spent fuel, otherwise lift the sphere to the top of the reactor by pneumatic means**
- **Distribute spheres to inner and outer core depending on burnup and reactor requirements (AVR & THTR)**
- **Spheres pass a number of times through the core (1-15) before reaching burnup limit. Number of passes influences the power profile and the amount of spheres circulated per day**

Fuel Discharge Operation

- Fuel determined to have reached their burnup limit are discharged to spent fuel storage
- Spent fuel storage can be in casks (HTR-Modul), drums (THTR) or tanks (PBMR)
- Storage geometry ensures subcriticality
- Decay heat can be removed by air or water cooling



Fuel Handling System Maintenance Modes

- **Online maintenance is possible for a majority of the components – The plant can operate without running the fuel circulation, loading and unloading for about 15~20 days**
  - Most actuators (except Isolation valves), burnup measurement system, gas blowers, filter, and broken sphere containers
- **Reactor must be depressurized for maintenance of**
  - Core unloading device (CUD), isolation valves

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AVR Experience

- **Circulated 2,400,000 Pebbles**
- **Charged/Discharged: ~ 300,000 Pebbles**
- **Overall Impact on Plant Unavailability <3% (higher initial period, later lower)**

Note: Low AVR Broken Sphere Rate: ~10^{-4} (and even better the latter part of life: ~$2x10^{-5}$) had significant positive impact on the reliability

Lessons Learned from AVR

- **Simplify sphere removal from core:**
  - 2 (redundant) Core Unloading Devices (CUD) that take over the function of the reducer, singularizer, and the broken sphere separator
- **Improve actuation method for various moving components**
  - Electro-pneumatic actuators for valves and indexers, diverters and collectors, mounted in functional blocks for easier maintenance, instead of the dosing wheel and elevator
- **Maintenance on AVR components can be done readily after some decontamination (dust is not a major issue)**

THTR Experience

- **Circulated: ~1,400,000 pebbles**
- **Charged/discharged: ~235,000 pebbles**
- **Overall impact on plant unavailability ~15% (higher initial, lower later)**
- **THTR completed the core unloading in 10 months, without major interruptions, demonstrating that the modifications to the FHS performed as designed**

Note: high broken sphere rate: initially~1.5% to later ~0.6% caused jamming in the FHS near the discharge of the CUD, Also required frequent exchange of the damaged sphere container. Broken spheres were caused by the in-core rod design that pushed into the bed.

Lessons Learned from THTR

- **Early troubles can be resolved – but more testing prior to plant installation reduces the downtime**
- **Dust is there, but has not been a maintenance/health-physics issue at either AVR or THTR**
- **Do not use in-core rods which causes high failure rate of spheres resulting in frequent exchange of broken sphere can and jamming in the sphere circulation system**
- **Excess reactivity in the core allows online maintenance of most of the system (15 to 20 day reactivity reserve)**
- **Many of the maintenance activities could be carried out when the plant was at power – Exceptions are isolation valves, CUD and broken sphere container**

Pebble Bed FHS Design Philosophy

- **Follow THTR's example to the extent practicable**
  - Functional blocks mounted in the floor
  - Components installed in functional blocks
  - All components monitored for leaks
- **Improve those components with known deficiencies**
  - Pebble counter
  - Core unloading device and lead-in plenum

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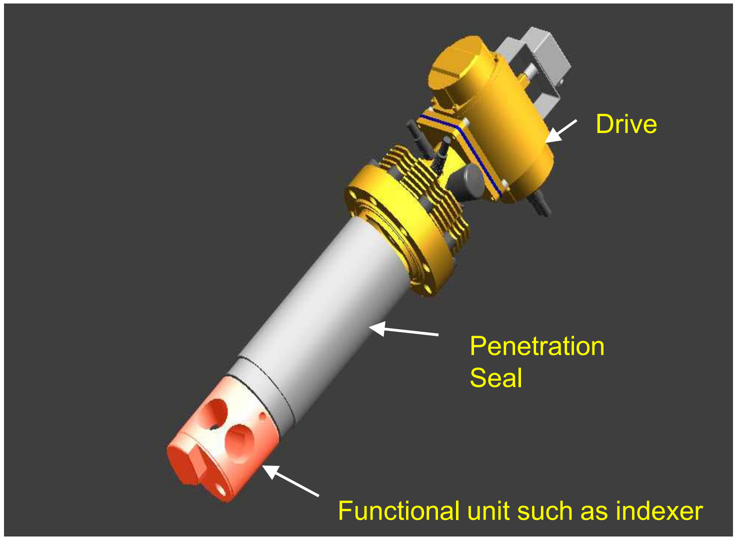
Typical Functional Block



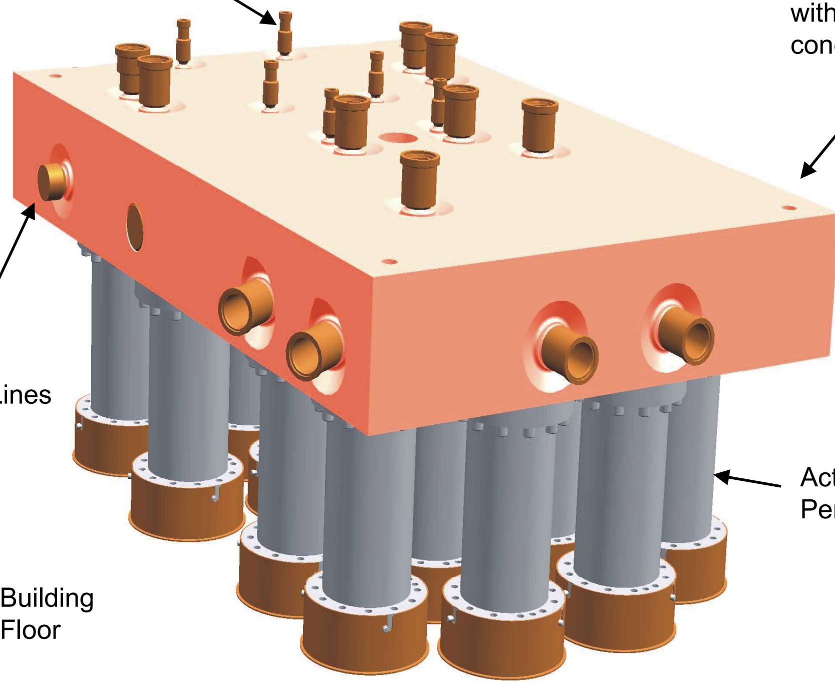
Building Floor

Actuator Inserts

Electro-Pneumatic Drives

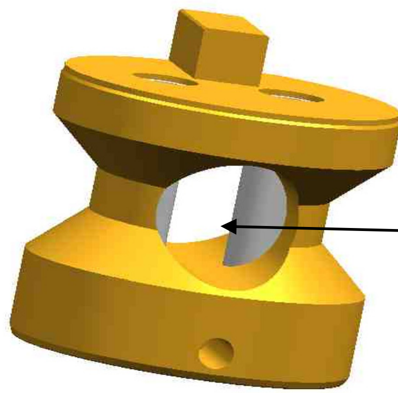
Leak Monitoring

Steel block filled with iron shot concrete



Pebble Lines

Actuator Penetrations



Pebble Pathway

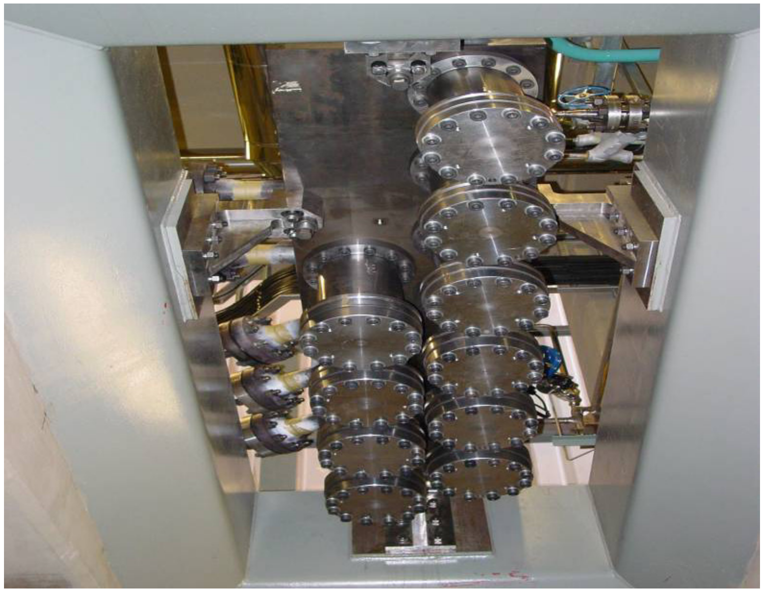
FHS Tests at the PBMR Helium Test Facility

- **System Tests**
  - Sphere circulation
  - System cleaning
  - System maintenance
- **Component Tests**
  - Core unloading device
  - Tank unloading device
  - Sphere valve and valve block
  - Sphere counters
  - Gas valves and valve blocks
  - Mechanical and pneumatic sphere brakes
  - Indexer and double-seat isolation valves
- **Burnup Measurement System testing done in Russia**

Note: These tests have been ongoing since 2006 and will continue up to qualifications tests when a reactor construction project is ordered

FHS Components under Test

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Summary

- **Refueling is accomplished on-line during power operation in a pebble bed reactor and provides core design flexibility**
- **Most maintenance activities on the FHS is accomplished on-line during power operation**
- **Good experience on the AVR and THTR of FHS operation and maintenance**
- **Lessons learned from AVR & THTR are incorporated in modern pebble bed FHS designs**
- **Full scale FHS circulation loop and components are under test at the PBMR HTF in South Africa**

Suggested Reading

- The Fuel Handling and Storage System (FHSS) Model for the Pebble Bed Modular Reactor (PBMR) Plant Simulator, T. Dudley et al, Proceedings of HTR-2006, October 2006, Johannesburg South Africa
- Design and Full Scale Test of the Fuel Handling System, J.G. Liu et al, Nuclear Engineering and Design, Volume 218, Issues 1-3, October 2002, Page 169-178
- The Measurement of Burn-up Level in the HTR-10, L. Zhengpei et al, Proceedings of the Conference on High Temperature Reactors HTR-2002, April 2002, Petten NL, p.1-5
- PBMR Nuclear Material Safeguards, J. Slabber, Proceedings of the 2nd International Topical Meeting on High Temperature Reactor Technology, September 2004, Beijing China