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Pebble bed reactor fuel cycle optimization using particle swarm algorithm

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HIGHLIGHTS

- Particle swarm method has been developed for fuel cycle optimization of PBR reactor.
- Results show uranium utilization low sensitivity to fuel and core design parameters.
- Multi-zone fuel loading pattern leads to a small improvement in uranium utilization.
- Thorium mixes with highly enriched uranium yields the best uranium utilization.

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ABSTRACT

Pebble bed reactors (PBR) features, such as robust thermo-mechanical fuel design and on-line continuous fueling, facilitate wide range of fuel cycle alternatives. A range off fuel pebble types, containing different amounts of fertile or fissile fuel material, may be loaded into the reactor core. Several fuel loading zones may be used since radial mixing of the pebbles was shown to be limited. This radial separation suggests the possibility to implement the "seed-blanket" concept for the utilization of fertile fuels such as thorium, and for enhancing reactor fuel utilization. In this study, the particle-swarm meta-heuristic evolutionary optimization method (PSO) has been used to find optimal fuel cycle design which yields the highest natural uranium utilization. The PSO method is known for solving efficiently complex problems with non-linear objective function, continuous or discrete parameters and complex constrains. The VSOP system of codes has been used for PBR fuel utilization calculations and MATLAB script has been used to implement the PSO algorithm. Optimization of PBR natural uranium utilization (NUU) has been carried out for 3000 MWth High Temperature Reactor design (HTR) operating on the Once Trough Then Out (OTTO) fuel management scheme, and for 400 MWth Pebble Bed Modular Reactor (PBMR) operating on the multi-pass (MEDUL) fuel management scheme. Results showed only a modest improvement in the NUU (<5%) over reference designs. Investigation of thorium fuel cases showed that the use of HEU in combination with thorium results in the most favorable reactor performance in terms of uranium utilization. The results revealed that neutronics characteristics of the PBR technology are only marginally affected by the fuel management choices.

1. Introduction

Pebble bed reactors (PBRs) are variant of the HTGR technology, where the fuel is in the form of pebble instead of the more common tall cylindrical fuel elements in prismatic blocks or fuel assemblies. PBRs are graphite moderated and helium cooled, hence may operate at high temperatures (~950 °C) which leads to high thermal efficiency. A large number (500–20,000) of tristructural-isotropic (TRISO) fuel particles are embedded in a 6 cm diameter graphite fuel pebble. The TRISO coated fuel particles which evolved over decades of research include a heavy-metal fuel kernel coated by 4 layers of 3 materials for fission product retention and isolation. PBRs are also characterized by inherent safety features due to the melt resistant graphite core structure and to the excellent fission-product retention capabilities of the TRISO fuel particles. These promising features promoted the HTGR and PBR technologies in leading research and development programs such as Generation IV International Forum (GIF) U.S., 2002and Next Generation Nuclear Plant (NGNP) NGNP, 2010.

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The spherical shape of fuel pebbles allows for on-line continuous refueling, where fuel pebbles are loaded to the top of the core and unloaded from the bottom. Typical cylindrical core designs contain from ~200,000 to ~1,000,000 fuel pebbles for 150MWe to 1000MWe reactor designs. Depending on fuel cycle design and refueling machine capabilities, loading/unloading rate can vary between ~300 and ~9000 pebbles/day (Teuchert, 1977). The continuous fuel management feature low excess reactivity, thus neutron poisons are not required and control rods are only needed for the startup and shutdown of the reactor. This leads to more efficient neutron economy and better safety. The drawback is the need for a complex refueling machine.

The AVR 15MWth research PBR operated from 1967 to 1988 at the Julich Research Center, gaining valuable experience which led to the construction of the THTR300, 300MWe commercial reactor in Schmehausen, West Germany. The THTR300 generated electricity from 1985 to 1989 with uranium–thorium fuels. It was closed and decommissioned due to a combination of technical and political problems (Baumer and Kalinowski, 1989). The HTR10 10 MWth research PBR at Tsinghua University in China achieved first criticality in 2003. The HTR10 is part of China's HTGR development program, and a scale-up demonstration plant, the HTR-PM 200 MWe started construction in 2009 (Zhang et al., 2009).

PBR fuel management includes the decisions on loading, discharging, storing, repossessing and disposal of fuel pebbles. The on-line refueling feature of PBR fuel management may be considered as part of the reactor control operations since whenever core reactivity drops, reactive fuel pebbles (fresh or partly burned) are inserted to maintain criticality. In this study, two PBR fuel management schemes where investigated (Fig. 1):

(1) MEDUL (MEhrfachDUrchLauf-"multi-pass" in German) fuel management implies discharge and re-introduction of fuel pebbles into the core several times (4–20 times) until reaching their target burnup. The reactor design includes a fuel recirculation system which detects the burnup level of the discharged pebbles (by gamma-ray spectrometry (Hawari et al., 2002) and controls the reshuffling operations. Pebbles which reach the target burnup level are discharged from the system (to spent fuel storage); otherwise they are reintroduced into the core. Hence, mixtures of fresh and partly burned pebbles are continuously charged into the core reducing the power peaking and lowering the axial power peak location. The MEDUL scheme features improved safety and more efficient neutron economy (reduced leakage).

(2) Once-Through-Then-Out (OTTO) fuel management scheme is where fuel pebbles are discharged for disposal after single pass through the core. The flow rate of the fuel pebbles is designed such that the discharged fuel burnup level will not exceed the permitted level. The OTTO scheme features a simpler design and operation, since it does not require a fuel reshuffling system. However, the OTTO scheme features higher power peaking with higher maximum power level located at the upper core region. Moreover, higher neutron flux at the core upper part may increase the differential control rod worth (reactivity change per unit length of insertion depth) at upper core area and reduce differential control rod worth at lower part of the core. For reducing the flux and power levels at the reactor top, several OTTO reactor designs introduce burnable poisons into the fuel.

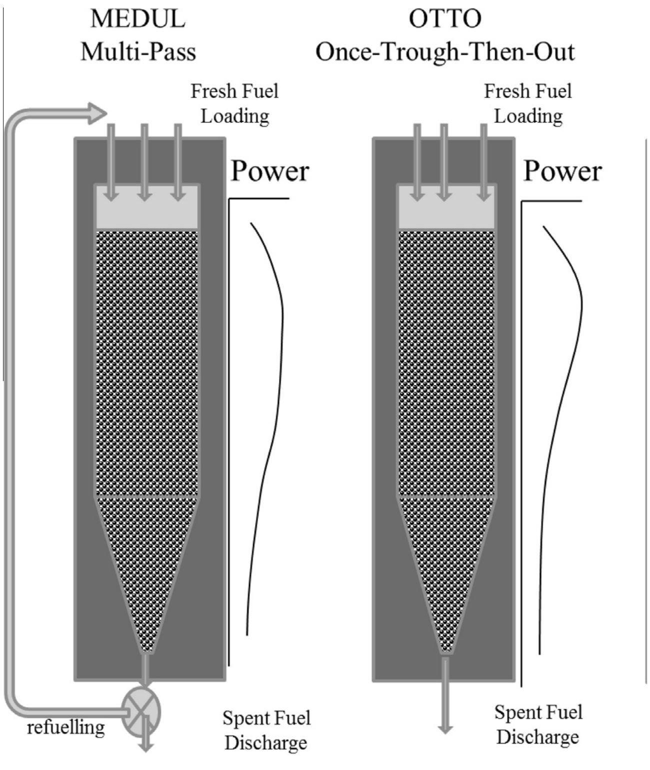

Fig. 1. Pebble-bed reactor fuel management schemes.

A number of previous studies Teuchert (1977), Mulder and Teuchert (2006), Shropshire and Herring (2004), Ferhat et al. (2007), Boer and Ougouag (2010) investigated different pebble geometric arrangements together with different fissile/fertile material content (U, Pu, Th) has been carried out in order to improve the reactor performance. These investigations demonstrate the flexibility of the PBR design.

Experiments and simulation of the pebble movement through the core revealed that the pebble flow is almost "laminar" – fuel pebble moves vertically downwards with negligible cross-flow (pebbles flow in "Channels"). Pebbles flow rate adjacent to the reflector is slightly slower, due to the increased friction; as ratio of core height to diameter increases, pebble flow velocity becomes uniform (slug flow). Hence, when loading several fuel pebble types to different radial zones, separation between fuel types is maintained along the core. The radial separation enables the implementation of the seed-blanket concept (Galperin et al., 1997), when loading seed and blanket fuel pebbles in separate channels.

The thorium based SBU (Seed Blanket Unit) fuel concept was originally proposed by Prof. A. Radkovsky for application to Pressurized Water Reactors (PWR) Galperin et al., 1997. In PWR cores, the idea is to separate spatially between fissile material (seed – enriched uranium) and fertile material (blanket – thorium). This separation is more neutronic efficient since at BOL it reduces the competition for neutron absorption between fissile and fertile nuclides resulting in more efficient breeding. When mixed homogenously, at BOL, uranium limits neutron absorption in thorium.

It has been shown (Reitsma, 2004; Teuchert et al., 1994) that implementation of the SBU concept in PWR decreases the amount of discharge spent fuel by up to 60%, for a given energy production, compared with standard slightly enriched LWR fuel cycle. The rate of plutonium production in the SBU cycle is only 30% that of a corresponding rate for standard PWR. The amount of heavy metal, required for cycle reload is significantly lower in SBU designs than in conventional PWR core. On the other hand, due to the high enrichment of the uranium (seed) fuel, the quantities of required Separative Work Unit (SWU) are larger. Consequently, the fuel cycle cost is almost the same for all considered designs. Also, in