Comparative Study of Spent Fuel Storage Design Aspects for HTR-PM and other Pebble-Bed HTGRs

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INTRODUCTION

Fuel elements of high temperature gas-cooled reactors (HTGRs) possess a large temperature margin below the design limit due to the ceramic coatings of their fuel particles and their graphitic shells. Pebble-bed HTGRs could circulate the fuels through the core before they reach the design burnup. The spent fuels are discharged into spent fuel containers by the fuel handling and storage systems. Spent fuel storage system for pebble-bed HTGRs should generally have the basic functions of shielding the nuclear radiation and removing residual heat of the spent fuels. Typical pebble-bed HTGRs, such as AVR[1], HTR-MODUL, PBMR, HTR-10[2], HTR-PM[3] and HTR-PM600[4] realize or design these functions in different ways. It is interested to compare their design features and main parameters and obtain suggestions on the future design of spent fuel storage facilities for multi-module pebble-bed HTGRs.

RESULTS

Fuel elements

The main parameters of fuel element for AVR, HTR-MODUL, PBMR, HTR-10, HTR-PM and HTR-PM600 are shown in Table I. All fuel elements of these reactors are spherical with coated particles in them, but they are different in some aspects. AVR tested diverse types of fuels, but only GLE-3 and GLE-4 types manufactured with improved TRISO particles are referred here. The heavy metal loading per fuel element of HTR-MODUL, HTR-PM and HTR-PM600 is limited to 7 g in order to restrict the reactivity increase in case of water ingress into the primary circuit. The spent fuel discharge burnup of most reactors is generally 80-100 GWd/tU. Experiments of AVR even extended the burnup of some fuels up to 160 GWd/tU to test the fuel cladding performance.

Decay heat of spent fuels

The discharged spent fuels of HTR-PM are held up in the fuel handling system for over 50 hours before stored in the spent fuel canisters. For HTR-10, this holding time could be as long as 36 days [5]. The initial power rate per spent fuel element when stored is 7.9 W for HTR-PM and 1.2 W for HTR-10.

TABLE I. Parameters of Fuel Element for Pebble-Bed Reactors

	Heavy Metal loading per fuel element (g)	U-235 enrichment of fresh fuel (mass %)	Average discharge burnup (GWd/tU)
AVR (GLE-3;4)	10; 6	9.82; 16.76	160
HTR-MODUL	7	7.8	80
PBMR	9	9.6	92
HTR-10	5	17	80
HTR-PM	7	8.5	90
HTR-PM600	7	8.5	90

Spent fuel containers

Spent fuels of AVR were stored in so-called AVR-cans and cooled in a water pool for about 2 years, and then decanted in the hot cells into dry storage cans. Each small AVR-can could hold 50 elements, while each dry storage can could hold 950. Both kinds of cans were made of stainless steel without sufficient shielding effectiveness. Two dry storage cans were placed in a CASTOR cask. The CASTOR casks, with 30-cm-thick cast iron shielding, could be used for transport and storage of spent fuels from AVR and THTR. They could be cooled by natural convection.

Spent fuels of HTR-MODUL are stored in shielded containers with 40-cm-thick cast iron. Each container can hold 30,000-60,000 spent fuel elements. The initial heat load per full container is 19 kW. The container could be cooled in freely circulating air.

The former scheme of PBMR for spent fuel storage was 10 large tanks, each with the capacity of 500,000 elements. The maximum decay heat load would be 48 kW per tank. Another proposed scheme is 12 tanks for wet storage for the first 8 to 9 years and 36 for dry storage thereafter, each with the capacity of 175,000 elements.

Each HTR-10 spent fuel storage tank could hold 2,000 fuel elements with the total heat load of 1.9 kW when it was just fully filled. The heat could be removed by natural ventilation in a concrete sleeve. The radiation from fuels could be shielded by the 13-cm-thick lead tank shell and the outer concrete sleeve.

The spent fuels of HTR-PM will be stored in stainless steel canisters. The canister could be filled with 40,000 elements. Its maximum thermal power rate is 30 kW. All the canisters will be stored in dry silos at the nuclear island and cooled by air. Specifically, fresh canisters will be stored in buffer region silos and cooled by forced air ventilation for the first 5 years. Then they can be moved to silos in another region and cooled by natural ventilation. The radiation shielding is mainly provided by the concrete around silos, since the steel shell thickness of canisters is only 2-3 cm.

HTR-PM600 will adopt the same design of fuel elements and similar scheme of spent fuel storage with HTR-PM. The silos could accommodate the generated spent fuels in 10 years for 6 reactor units.

DISCUSSION

Spent fuel dry storage with high safety margin, material friendliness, easy maintenance and economical efficiency, is getting more attractive than wet storage. Dry storage is also more appropriate for fuel elements of pebble-bed HTGRs. It is feasible for small reactors such as HTR-10 to store spent fuels and remove their decay heat passively by air immediately after they are unloaded. However, when the thermal power rate of the reactor increases, forced cooling (such as HTR-PM and HTR-PM600) or water cooling (such as PBMR) for spent fuels needs to be introduced. The HTR-PM and HTR-PM600 with silo structure utilize the chimney effect in order to reduce the necessary time of forced cooling and switch to natural cooling soon.

Containers for spent fuels are either shielded tanks or unshielded canisters. Fully shielded tanks could be directly transported if their size is limited. Spent fuels stored in oversized tanks should be retrieved before transportation. Unshielded canisters need to be handled with additional shield. Unshielded canisters with proper sizes could be economically attractive to large-scale reactors, because massive shielding material could be saved and space could be left to store more fuels. The canisters can also be directly loaded into shielded casks and transported while the spent fuels inside are free from retrieving.

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