Fuel Cycle Performance of Thermal Spectrum Small Modular Reactors

1. Introduction

Small modular reactors (SMRs) is a smaller nuclear fission reactor. With the decreasing of size, it provides several economic benefits such as it requires smaller power grid and the construction of the plant is cheaper. On the other hand, SMRs are manufactured and assembled on a factory location which reduced on-site assembly processes and facilitates the installing. Moreover, as SMRs are smaller, there is a possibility to have underground placement of the reactors and spent-fuel storage pools which also provides better security.

Different from the light water reactor, the size of the SMRs are about half and thus are forced to have less batches of their fuel assemblies. The position rotation of the batches is because of the uneven burnup in the core. In a PWR, for example, there are three batches of fuel assemblies in order to obtain its highest enrichment. Every 18 to 24 months, one batch (⅓ of the fuel assemblies) will be removed and the other ⅔ will be replaced.

2. Problematic

As the number of assemblies in SMR is limited by its size, it is difficult to arrange them in their most efficient way. There is an increase of neutron leakage so decrease of reactivity, forcing the SMRs to be less efficient while producing more waste. In this study, the calculations focus on thermal spectrum light water SMR. A one-batch 37 fuel assemblies in a once-through fuel cycle.

3. Simulation of PWR as reference

In order to have a starting point for the SMR model, a simplify PWR core equilibrium was calculated. The code used was PARC that calculate equilibrium cores with a discharge burnup convergence criterion of 0.1 GWd/t. For the simulation only one enrichment was used (4.9 %) and has only one burnable absorber (ZrB2 coating); the equilibrium was reached keeping in account temperature, moderator density and temperature, and soluble boron - calculated iteratively in each burnup step – feedback. For each of the three batches the fuel assemblies were relocated in the core, and the average final burnup was 53 GWd/T.

4. Simulation’s simplified model

Numerical simulations try to reproduce the real conditions as much as possible. However, one must find balance between the detail level of simulation and resources capacity. This fact explains the need of introduction of model simplifications. Moreover, there is no exact technical data on the SMR design then some assumptions must be made. The fuel assembly geometry remained the same but the core size has diminished. As a consequence, number of fuel assemblies was reduced alongside core height. Furthermore, the axial neutron reflectors were omitted. From a neutronic point of view, fuel consist of equally enriched uranium (max 4.9%). In order to control reactivity, instead using traditional Gd2O3, ZrB2 was used as a burnable poison.

All calculations were conducted assuming conservative values of neutron leakage. Even with this constrain, calculations of critical boron concentration at HZP are consistent with the NuScale
design value (1456 ppm vs 1303 ppm, respectively). Relative error (10.5%) was described as reasonable agreement by the authors.

5. Results and Discussions

In order to grade the performance of the SMR its natural uranium requirement was compared with value of PWR reference simulation, EG01. Two different cases of SMR core power were investigated in order to match average linear powers corresponding to one of AP1000 (18.75 kW/m; 400 MWt) and separately the NuScale SMR project (7.48 kW/m; 160 MWt). Both cases show very poor efficiency of natural uranium utilisation in comparison to reference project - average discharge burnup of higher power case is 30.5 GWd/t (resulting in required natural uranium resources of 366.04 t_natU/GWe-year) and in NuScale model - 32.4 GWd/t (respectively 344.58 t_natU/GWe-year). This results are nowhere near neither typical 3-batch PWR - 50 GWd/t (requires 188.63 t_natU/GWe-year) - nor one-batch version - 44.35 GWd/t (253.73 t_natU/GWe-year).

Such values results dominantly from limited geometrical dimensions of the core, what causes much higher neutron leakage from the core region than in case of typical PWR. Second important factor is high flux gradients within the core, resulting in strongly uneven burnup of the fuel assemblies and as the consequence decreased average discharge burnup (inefficient fuel usage). Third important factor is one-batch loading scheme (with homogenous enrichment of FAs), which makes efficient uranium utilization even more problematic challenge (heterogeneous enrichment in PWR allows to flatten the shape of radial flux).

Separate calculations were performed in order to determine the influence of SMR core size on its performance. It is not surprising that increase of the core size allows to vastly decrease the core leakage and increase the average discharge burnup, what obviously results in more efficient fuel utilisation.

6. Conclusions

According to the above study, when comparing SMRs and LWRs it can be stated that SMRs achieve lower discharge burnup, thus the uranium utilization is reduced. These occur due to the higher neutron leakage, single-batch cores and heavy use of burnable neutron absorbers. Moreover, the heavy use of burnable poisons and control rods causes hardening of neutron energy spectrum, which in turn leads to the increase of transuranic isotopes fractions in discharge isotopic vector and, more importantly, to the increase of the decay heat, toxicity radioactivity of the spent nuclear fuel. In addition, the hardening of the neutron spectrum limits the vessel time-life due to increased irradiation. Economically, the cost of a SMR’s fresh fuel per bundle is higher than that of a LWR. This comes from the complexity of the fuel fabrication, since SMR fuel characterises in additional radial and axial heterogeneity. Last, but not least, the environmental metrics. The use of the SMR technology over the LWR technology increases environmental impact, e.g. land use, water use and carbon dioxide emissions.